International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Autonomous UAV Networks Based on Artificial Intelligence

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A B S T R A C T

UAV developments in recent years have ensured that UAVs would be an inherent part of the upcoming networking and communication systems. Several studies have recommended UAV-assisted solutions to improve conventional networks' performance, offering more coverage and capacity to the consumers. However, the comprehensive study on the AI-based autonomous UAV network design subfields remains to be fully established. This study provides a systematic analysis of the AI-based autonomous UAV networks. This analysis was carried out on a sample of more than 100 published articles on UAVs, focusing on the autonomous capability classification, network resource provision, network planning and selection, multiple access and routing protocols, power control, and power consumption strategies in UAV networks. It could be ascertained from the review and analysis of the previously existing literature on UAV networking that AI-based UAVs are a profitable and technologically sound choice for future networks. This shall aid in the swift designing of the cost-effective choices, while also deploying them as the next generation of autonomous networks. Finally, we have also identified the research issue for future research programming in the UAV networks. It is also hoped that this review shall encourage more research projects for the construction of low-cost and energy-efficient future UAV autonomous networks.

Keywords: Artificial intelligence; autonomous UAV; AI-based UAV networks

1. Introduction

The burgeoning interest in unmanned aerial vehicle (UAV) *[109]* networks has recently captivated the network research community. Various studies have focused on the development and performance evaluation of UAV networks [1,2]. These networks are primarily employed to navigate challenging terrains that traditional communication networks cannot cover. UAV networks excel in delivering superior performance through optimized topology, spectral efficiency, and situational awareness. With minimal human oversight required in UAV network operations, researchers are increasingly turning to artificial intelligence (AI) to efficiently manage these networks, developing various applications through machine learning for both scholarly and commercial use.

The central question addressed in this review is: How can a comprehensive literature survey on AI-driven autonomous UAV networks be structured? In response, we have reviewed over 100 papers on UAVs that explore autonomous characteristics, network planning, resource management, access protocols, and energy efficiency. We discuss AI-based UAV networks in the following sections.

1.1. AI-Based UAV Networks

AI is employed to create methods that emulate or surpass human cognitive abilities, crucially learning and adapting [3]. Given their dynamic nature and complex challenges, UAV networks are ideal candidates for AI application. This ongoing research spans several critical areas including security, network architecture, and applications essential for advanced UAV network deployment.

1.1.1. Security and Privacy Concerns

Security and privacy are significant concerns in wireless networks, especially those like UAV networks with constantly changing topologies. Numerous studies address these issues using AI strategies, with some proposing AI-based solutions for cyber and physical threats using convolutional and recurrent neural networks to analyze high-risk areas and UAV motion [4]. An intriguing study demonstrated how a UAV swarm could maintain terrestrial coverage effectively through local communications while mitigating cybersecurity risks [5].

1.1.2. UAV Network Design Challenges

UAV networks, unique in their attributes, require bespoke solutions unlike those applicable to other networks such as MANETs and VANETs. A novel autonomous flock control technique has been proposed to support UAV swarms by maintaining an energy-efficient topology using principles from

Reynolds' Boid model [7]. Other wireless challenges tackled include enhancing reliability, reducing latency, and improving handover and path planning through various AI applications [4].

1.1.3. Localization and Trajectory

Challenges in localization and trajectory are prominent when dealing with UAVs. A recent innovation introduced AI-enabled trajectory planning using a quantum mechanism, proving more effective than traditional Q-learning approaches [9]. An intelligent localization method for UAV swarms has also been developed, which minimizes localization errors and speeds up network convergence by implementing an energy-efficient routing algorithm [10].

1.1.4. General Applications

Research into UAV networks extends to their integration with cellular and vehicular networks, coverage of high-risk zones, and spectrum utilization. Notably, UAV networks have been shown to enhance VANET performance, with novel routing protocols improving vehicular reliability and aiding in the detection of malicious vehicles [11]. The results indicate a significant enhancement in identifying harmful *vehicular activities*

1.2. Overview of Recent Literature Reviews

The field of autonomous UAV networks has seen a proliferation of innovative technological approaches recently, prompting extensive reviews of existing literature to comprehensively understand these advancements. This section covers some of the most pertinent surveys recently conducted in this area.

UAV coverage remains a critical area of study. Several technologies have been introduced to enhance the coverage capabilities of UAV networks. A comprehensive review [12] discusses various challenges related to UAV network coverage, categorizing these challenges and considering multiple constraints. The review emphasizes the urgent need for more detailed research to explore coverage issues within and between UAV networks as well as to address latency and reliability concerns.

A 2015 survey [13] explores the distinctive attributes of UAV networks that differentiate them from conventional ad hoc, vehicular, and other wireless networks. This survey examines the challenges across different network layers—physical, data link, network, and transport—specific to UAVs, characterized by their dynamic nature and intermittent connections. The findings advocate for cross-layer design approaches tailored to the unique requirements of UAV networks, particularly in dynamics and energy efficiency.

Channel modelling for UAV networks is thoroughly examined in another study [14], where the authors delve into the specific requirements for effective network performance and design, particularly focusing on low-altitude platforms. This survey investigates cost-effective and low-power solutions for channel propagation both in the air and to the ground.

The integration of 5G millimetre wave technology with UAV networks is the focus of another survey [15], which proposes a novel classification of recent developments into seven categories, ranging from antenna technologies to performance evaluations. This survey pinpoints numerous emerging research opportunities and practical considerations to enhance the efficacy of UAV networks for both industrial and academic purposes.

A recent survey [19] provides an in-depth review of UAV network applications, offering a detailed classification of these networks into nine categories and discussing the three levels of autonomy that define their operations. This paper also reviews current challenges and future trends.

From a security perspective, a survey [20] explores critical issues like sensor faults, unreliable communications, and potential data breaches in UAV networks, suggesting adaptations of techniques from mobile ad-hoc and vehicular networks to address these concerns.

The use of machine learning techniques in UAV networks is comprehensively reviewed in surveys conducted in 2019 [21] and more recently [22]. These reviews classify ML strategies and discuss their implementation to optimize UAV network performance, especially when integrated with mobile-edge computing for enhanced reliability and efficiency.

Lastly, a study [23] details the methodologies for developing UAV network prototypes and experimental setups, covering all stages from aircraft selection to communication protocols, and suggests the future integration of machine learning and 5G technologies to advance UAV communication systems. Table 1 summarizes these related surveys.

Table 1. Summary of Recent Literature Reviews

Survey Scope	AI-Inspired?	UAV Features Addressed	Limitations	Reference
Cooperative UAVs, system deployment	Yes	Coverage, deployment, and nodes used	Obstacles in coverage are not considered	[12]
Various UAV networks, routing	Yes	Topology, mobility, reliability, and energy efficiency	System optimization has not been explored	[13]

UAV channel modeling, low altitude	Yes	Channel measurement and characteristics, fading	UAVs in dense urban areas are not explored	[14]
UAV-assisted and 5G mm wave communications	No	UAV as aerial access, relay, and backhaul	Antenna design, channel modeling, and performance assessment	[15]
Routing protocols for UAV networks	No	Topology, position, and cluster-based routings	UAV routing such as link disconnection has not been explored	[10]
Integration of UAV and cellular networks	Yes	UAV categorization, standardization, aerial channel modeling, and security	UAV antenna design has not been explored	[17]
UAV software-defined network (SDN) and network function virtualization (NFV)	Yes	SDN, NFV, cellular communication, routing, and monitoring	Wireless power transfer has not been addressed	[18]
Applications of multiple UAV systems	Yes	Coordination, cooperation, system autonomy	Multiple UAV systems have not been explored	[19]
Safety, privacy, and security issues of UAVs	No	Sensor-based attacks, GPS jamming, spoofing, and multi-UAV-based security	UAV privacy and security have not been addressed well	[20]
Machine learning for UAV communications	Yes	Channel modeling, positioning, resource management	UAVs for vehicular networks not addressed	[21]
UAV-centric machine learning	Yes	Cooperation trajectory planning, channel modeling, mobile-edge computing	Traffic dynamics and channel conditions not explored	[22]
UAV prototyping and experiments	No	Cellular UAVs, interference mitigation	Path planning optimization not explored	[23]
UAV Channel modeling, link budget	No	Two-ray fast fading, Rician fading, Rayleigh fading	UAV with satellite not explored	[24]

1.3. Main Contributions

This paper's primary contributions are outlined as follows:

- We perform a detailed review and analysis of over 100 research articles from academic journals and conference proceedings concerning UAVs.

- We organize the existing studies on UAVs by their autonomous characteristics, concentrating on the examination of network resource management, multiple access and routing protocols, and power control and energy efficiency, which are crucial for developing and implementing future autonomous UAV systems.

- We pinpoint and elaborate on potential open research topics such as UAV network coverage, MAC protocol formulation, AI algorithm development, and issues related to security, safety, and privacy management.

1.4. Paper Structure

The layout of this paper is depicted in Figure 1. Section 1 introduces AI-based UAV networks and summarizes previous surveys on the subject, including a highlight of the main contributions. Section 2 covers the foundational background of the survey, discussing autonomous UAV networks, their communication, computation, control, channel modeling, and interference management. The review of autonomous UAV features, resource management, network planning, multiple access and routing protocols, power control, and energy efficiency is detailed in Section 3. Section 4 is dedicated to the exploration of security, safety, and privacy management, including aspects of physical layer security. The hallenges and future research directions are explored in Section 5, with the paper concluding in Section 6.

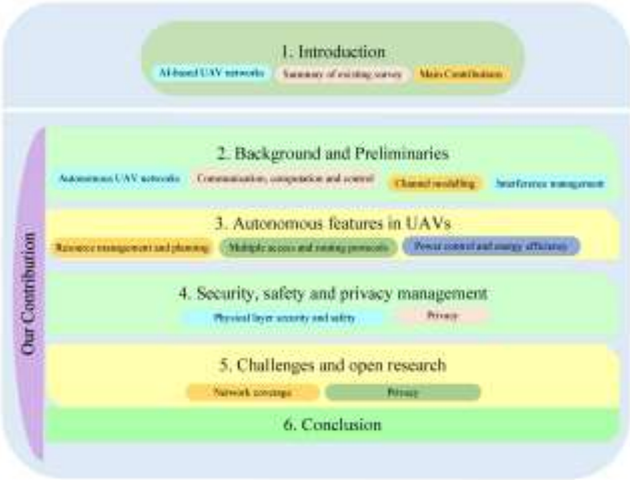

Figure 1. Structure and organization of this paper.

2. Background and Preliminaries

Unmanned Aerial Vehicle (UAV) networks present a novel communication approach distinct from traditional methods. This section outlines the foundational concepts and initial considerations in the development of UAV networks.

2.1. Traditional versus Autonomous UAV Networks

According to Business Insider [25], the drone industry is projected to reach USD 63.6 billion by 2025. The origins of UAVs trace back to World War I in 1917 [26], where challenges in accuracy, privacy, and communication rendered UAVs unreliable for extensive use. Over time, with progressive research, more dependable solutions for UAV networks have been developed. This discussion, however, focuses on contemporary applications of UAV networks implemented in recent years. UAVs are increasingly utilized in fields such as telecommunications, surveillance, security, and military operations due to their cost-effectiveness and adaptability. These networks are particularly advantageous in complex environments like riverbanks, mountainous areas, and forests. The aerodynamics of UAVs is crucial for their operation. UAVs are primarily categorized into fixed-wing UAVs (Figure 2a) and multi-rotor UAVs (Figure 2b) [27]. Multi-rotor UAVs, also known as rotary wing UAVs, rely on several rotors to create lift through vertical thrust, typically featuring 2 to 8 motors. These UAVs consume a significant amount of energy due to their vertical take-off and landing capabilities. Conversely, fixed-wing UAVs are more energy-efficient, utilizing gliding mechanisms to conserve energy and generally requiring runways for take-off and landing. Contemporary UAV networks often employ both types of UAVs to leverage their respective advantages.

Figure 2. Commonly used UAV. (**a**) Fixed-wing UAV [29] and (**b**) multi-rotors UAV [30].

2.2. Communication, Computation, and Control

Unmanned Aerial Vehicles (UAVs) have significant utility in various daily applications. The idea of UAV cooperation has been introduced to augment the functionalities of individual UAVs, sparking numerous studies on the potential benefits of UAV networks.

Reference [31] introduces a decentralized predictive control model applied to a group of UAVs. Simulations indicate that this model is more computationally efficient than centralized methods.

Research by Bellingham, J. et al. [32] develops a control system to enhance the coordination of multiple UAVs, tackling critical issues like trajectory optimization, resource distribution, and objective setting. Their strategy integrates these elements to improve the management of the UAV group, facilitating cooperative pathfinding and multitasking.

The potential for conflicts within UAV groups is addressed in a study presented in [33], which offers a model to detect and resolve such conflicts. This model uses intermediate waypoints and velocity controls, and is shown to be both scalable and rapidly implementable through simulations and experiments. Another investigation [34] suggests using thermal lift to extend the endurance of cooperative UAVs, demonstrating substantial potential improvements.

2.3. Channel Modelling

Channel modeling is essential for the integration of UAVs into the aerospace sector. UAVs are predicted to become commonplace in the near future, making the study of their channel use crucial. A thorough analysis conducted in 2019 [24] breaks down UAV channel utilization into three types: air-to-ground, air-to-air, and ground-to-ground, discussing aspects like link budgeting and channel fading. Another survey [14] examines the temporal and spatial properties of nonstationary channels, highlighting under-researched areas such as airframe shadowing and offering statistical models to aid in UAV communication. To better UAV communication in shadowed areas, a new, simpler channel model is proposed in [35], tested against empirical data to verify its efficacy.

2.4. Interference Management

Interference is a critical factor in wireless communications, significantly impacting UAV network performance. Recent studies focus on interference management, viewing UAVs as extensions of cellular networks or integrating them with power control strategies. In [36], a protocol that optimizes path planning to reduce latency and interference in ground networks is analyzed, using a game-theoretic interference mitigation strategy and deep reinforcement learning. A similar approach is taken in [37], where the focus is on maximizing UAV energy efficiency while reducing latency and interference, employing game theory.

Research in [38] explores UAVs supporting integrated access and backhaul (IAB) of cellular networks to diminish interference, framing the task as an optimization problem to maximize overall network performance, achieving superior results compared to existing methods. Power control is also pivotal in managing interference. A machine learning model employing K-means and affinity propagation is introduced in [39] to control UAV power and placement effectively. Zhang, S. et al. [40] split the issue into determining optimal transmit power and trajectory planning. Zhang, J. et al. [41] not only consider power control but also integrate UAV clustering into their game-theoretical approach to maximize network rates.

3. Autonomous Features in UAV Networks

The introduction of autonomous capabilities into UAV networks aims to optimize specific network problems while accommodating their dynamic nature. This includes designing features like resource management, multiple access protocols, and energy-efficient power control, as categorized in Figure 3.

These innovations are central to enhancing UAV network performance and adapting to evolving demands.

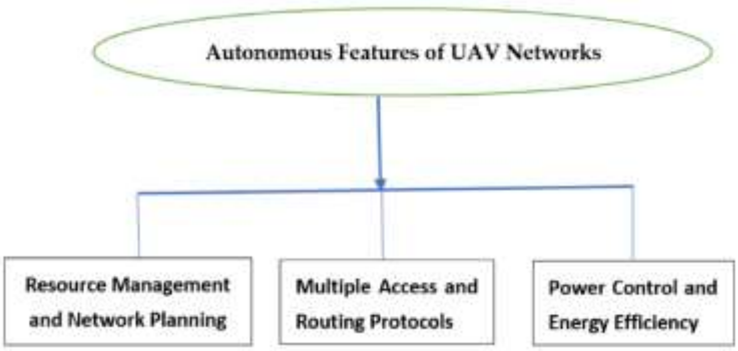

Figure 3. Autonomous features classification for UAV networks.

3.1. Resource Management and Network Planning

Effective management and strategic planning of network resources are essential for the performance of any network, especially those with limited human oversight. This is particularly significant in the context of UAVs, where numerous researchers are concentrating on this aspect. They are recognizing and tackling various challenges. Table 2 summarizes the surveys related to UAV network resource management and planning.

Table 2. Summary of related survey: UAV network resource management and planning.

Scope	**Autonomous Features**	**Computational Intelligence**	**Channel Modeling**	**Interference Management**	**Security and Safety**	**Reference**
Channel modeling		√	Shadowing channel	√	-	[35]
Interference management	Path planning	√	Rician distribution	√	-	[36]
Interference-aware path planning	Path planning	√	Free-space path loss with 6 GHz	√	-	[36]
Interference management	Spatial configuration	√	Customized	√	-	[38]
Interference management	Transmission power, trajectory planning	√	Large-scale path loss	√	-	[40]
Interference management	Transmission power	√	Free-space path loss	√	-	[41]
Resource management	Energy consumption, transmission power	√	Various	√	-	[42]
Resource management	User association	√	Free-space path loss	√	-	[46]
Delay-aware throughput maximization	Trajectory planning	√	Free-space path loss	-	-	[47]
UAV placement	Energy efficiency and optimization	√	Path loss outdoor/indoor penetration	-	-	[48]
Collision free navigation	Trajectory planning	√	-	√	-	[49]
Swarm-based UAV	Path planning	√	-	-	-	[50]
Physical layer security	security and cooperation	√	Free-space path loss	√	√	[51]
Secure UAV communication	Cooperative scheduling	√	Free-space path loss	-	√	[52]
Physical layer security	Cooperative trajectory and optimization	√	Free-space path loss	√	√	[53]
Physical layer security	Cooperative resource allocation	√	Free-space path loss	-	√	[54]
Quality of Experience (QoE)	Cooperative resource allocation	√	LOS and Non-LOS	-	-	[55]

In a study cited as [42], researchers are exploring how to efficiently manage resources in UAV networks using game theory. They discuss five different game theory models—coalition, potential, graphical, mean-field, and Stackelberg—each chosen for its relevance to specific goals, utility functions, and strategic applications in UAV operations.

Another paper, [43], investigates real-time UAV path planning in dynamic environments. It utilizes a discrete algorithm and a probabilistic graph to design collision-free routes. A similar approach is taken in [44], where information from both static and dynamic environments is integrated to refine UAV path planning. This study introduces an adaptive technique aimed at optimizing the path planning process.

Additionally, a noteworthy concept from [45] considers UAVs as new participants in 5G cellular networks. This inclusion presents several challenges for service providers who need to accommodate these new users efficiently.

3.2 Multiple Access and Routing Protocols

Access and routing protocols pose significant challenges in UAV networks. Initially, UAVs predominantly used space division multiple access techniques due to their co-location with other networks. However, researchers are increasingly investigating more efficient alternatives, such as orthogonal, non-orthogonal, and rate-splitting techniques. A summary of these can be found in related literature surveys.

Orthogonal Multiple Access (OMA) techniques minimize interference by ensuring that communications are mutually non-interfering. Various studies have explored time division (TDMA), frequency division (FDMA), code division (CDMA), orthogonal frequency division (OFDMA), and space division (SDMA) access methods. The downside to OMA is its limited spectral efficiency due to the finite number of non-interfering channels available.

Non-Orthogonal Multiple Access (NOMA) techniques address these limitations by optimizing base station functions such as power settings, flight paths, and positioning. NOMA can support more users on overlapping but correlated channels, but its performance might suffer if the number of antennas exceeds the number of users.

Rate-Splitting Multiple Access (RSMA) techniques aim to bridge the benefits of both OMA and NOMA. These techniques involve coordinating rates among multiple UAVs to maximize network performance, and have been the subject of extensive research.

3.3 Power Control and Energy Efficiency

For drones and UAVs, managing power and optimizing energy usage are crucial due to their aerial nature. Researchers have proposed various solutions to enhance power control and energy efficiency. These solutions include the use of multiple power sources such as batteries, hydrogen fuel cells, solar panels, and hybrid systems. Additionally, studies have looked into maximizing energy efficiency, which is vital for all UAV operations.

UAV Placement and Path Planning: Optimal UAV placement and efficient path planning are critical for energy management. Techniques explored include sample-based planning, comprehensive space searches, and biologically inspired algorithms. These methods aim to refine the trajectory and positioning of UAVs to conserve energy and enhance overall operational efficiency.

Table 3. Summary of related survey: UAV multiple access and routing protocols.

Scope	**Autonomous Features**	**Computational Intelligence**	**Channel Modeling**	**Interference Management**	**Security and Safety**	**Reference**
Channel access	Cyclic multiple channel access	√	Free-space path loss with LOS	-	-	[61]
MAC protocol	Energy consumption, Packet-error-rate (PER)	√	Free-space path loss with LOS	-	-	[62,63]
Performance evaluation of MAC	PER	√	Rician fading	-	-	[64]
Trajectory optimization	Trajectory planning	√	Free-space path loss with LOS, correlated Rician fading, Rayleigh fading, Rician K-factor	√	-	[67]
mm wave UAV cellular network	Beam forming	√	Quasi-static, Rayleigh fading	√	-	[68]

Channel access with time-modulated array (TDM)	Beam forming, performace	√	Free-space path loss with LOS	√	-	[70]
Trajectory optimization	Trajectory planning, power control	√	Additive white Gaussian noise (AWGN)	√	-	[74]
MAC protocol	Power optimization	√	Rician fading	√	-	[75]
MAC protocol	Throughput optimization	√	Free-space path loss	-	-	[76]
MAC protocol	Power optimization	√	Free-space path loss with LOS	√	-	[77]
MAC protocol	Trajectory planning, resource management	√	LOS and Non-LOS (NLOS)	√	-	[78]
MAC protocol	Power optimization	√	LOS, NLOS	√	-	[79]

4. Security, Safety, and Privacy Management

As technology advances and becomes more widespread, its security can be put at risk. Managing security, safety, and privacy is increasingly critical, and we need to do so with great care and efficiency. This topic is divided into two main categories, as illustrated in Figure 4.

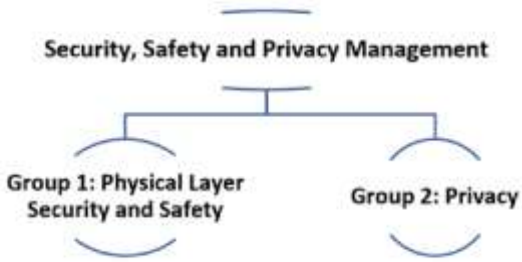

Figure 4. Security, safety, and privacy classification of UAV networks.

4.1 Physical Layer Security and Safety

We can broadly define physical layer security as methods used to protect communications over a channel from different types of attacks, such as eavesdropping or jamming. Figure 5 shows two common scenarios for UAV communication that illustrate this concept.

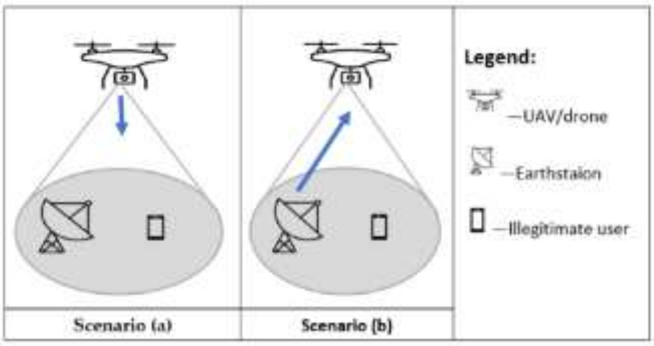

Figure 5. UAV communication scenarios: (**a**) UAV communicating to a ground station, (**b**) ground station communicating to UAV.

Figure 5a depicts a scenario where a UAV is attempting to communicate with an Earth station, which makes it relatively easy for unauthorized users to intercept the communications. Conversely, when the Earth station initiates communication with the UAV, intercepting these communications becomes more challenging. Scenario (b), shown in Figure 5b, inherently offers better security than Scenario (a).

To address these security vulnerabilities, one approach is to detect and track any potential eavesdroppers. This has been the focus of several studies, which suggest solutions like installing cameras or radars to monitor suspicious activities. Another strategy involves deploying anti-jamming techniques that introduce interference signals to thwart eavesdroppers, as discussed in various research papers.

Both scenarios in Figure 5 represent passive eavesdropping attacks, where the eavesdropper silently intercepts communications. However, active eavesdropping, which involves direct interference with communication channels, poses a greater threat. To counter this, strategies such as optimizing UAV flight paths and resource distribution have been proposed. These adjustments aim to weaken signals to unauthorized receivers while ensuring robust communication to intended recipients. Moreover, limiting the onboard resources available to UAVs can help minimize vulnerabilities and secure communications around key ground nodes. A summary of these methodologies and their effectiveness in enhancing UAV security, safety, and privacy can be found in Table 4.

Table 4. Summary of related survey—UAV security, safety, and privacy management.

Scope	**Autonomous Features**	**Computational Intelligence**	**Channel Modeling**	**Interference Management**	**Security and Safety**	**Reference**
Resource management	Energy consumption, trajectory planning	√	Free-space path loss with LOS	-	-	[65]
Computation optimization with energy management	Computation performance, energy consumption	√	Block-fading, LOS	√	-	[66]
Electric UAV, Fuzzy state machine	Energy management	√	-	-	-	[87]
Compressed hydrogen, fuel cells	Energy management	√	-	-	-	[89]
Hydrogen, fuel cells	Energy management	√	-	-	-	[90,93]
Solar power	Energy management	√	-	-	-	[91,92]
hybrid fuel	Energy management	√	-	-	-	[94]
UAV backhaul network	Energy efficiency, placement optimization	√	Free-space optical link (FSO), LOS	√	-	[95]
Secure UAV communication	Jamming power	√	Free-space pathloss with LOS	-	√	[103]
Co-channel interference management	Transmission power	√	Free-space path loss with line of sight (LOS)	√	-	[39]

Another area of research that some investigators are exploring is the defense of networks against unauthorized UAVs or drones. This issue typically arises when UAVs not belonging to a given network inadvertently intercept communications or when they are intentionally used for eavesdropping purposes. In these situations, these UAVs are external to the network and should not have the ability to capture its communications. To combat this problem, numerous studies have suggested the use of reinforcement learning techniques [56] and various detection strategies to pinpoint these unwanted UAVs within the network [57].

4.2. Privacy

Privacy remains a crucial concern for both our society and our community. While UAVs and drones offer several benefits due to technological advancements, they also pose a significant threat to individual privacy. Several research papers [104, 105] have been undertaken to examine public perceptions concerning drones and the impact of these devices on personal privacy.

A particular study [106] aims to rehabilitate the reputation of UAVs and drones concerning privacy invasion. The authors of this study argue that drones do not employ any novel technology; instead, they utilize a combination of pre-existing technologies that have already received privacy approvals. The paper recommends perceiving UAVs and drones as standard aircraft which, due to their unmanned nature, require cameras for operation. It also identifies UAVs and drones as major nodes for data collection, although the resolution of the images they capture is reportedly not high enough to compromise personal privacy significantly.

5. Challenges and Open Research Areas

Unmanned aerial vehicles (UAVs) are a burgeoning field of research. Despite various studies noted in networking literature, the performance issues and systemic challenges within this area remain unresolved. The following are highlighted as significant challenges and potential research opportunities:

5.1. Network Coverage

Research has been ongoing to enhance UAV network coverage, yet noticeable coverage gaps are observed especially when UAVs operate at lower speeds [107]. This presents an open area for research, potentially involving modifications to existing mobility models to boost coverage.

Additionally, emerging technologies like 5G coupled with UAVs can provide network coverage in areas immediately following disasters such as earthquakes and tsunamis. This is another vital research area where UAV-mounted cellular bases could be strategically employed.

5.2. MAC Protocol Design

Selecting an appropriate MAC protocol is critical for the efficiency of UAV-integrated networks. Various adaptations of traditional MAC protocols have been proposed to better suit UAV requirements. Nevertheless, for optimal efficiency, MAC protocols need to be specifically designed for UAV networks, possibly incorporating cognitive radio technologies.

5.3. AI Algorithm Design

Given that UAV operations often do not involve direct human intervention, the implementation of AI is indispensable. Deep learning applications could be specifically tailored to UAV-centric tasks such as emergency responses, event coverage, and servicing rural communities to achieve the best system performance.

5.4. Privacy and Security

As previously mentioned in Section 4 Scenario (b), the use of cameras on UAVs raises significant privacy concerns. This gap in research could be filled by integrating alternative technologies like LiDAR along with other sensors. A recent publication [108] addresses this concern, suggesting a focus on privacy enhancements could provide additional benefits. Furthermore, the integration of blockchain technology could bolster security measures for communications between drones and from users to drones.

The implementation of a blockchain framework could serve as a security layer for UAV communications, addressing both drone-to-drone and user-to-drone data exchanges. This is a crucial area for future research focused on securing UAV systems.

6. Conclusions

This paper presents a detailed survey on AI-based autonomous UAV networks, highlighting essential aspects such as autonomous features, network management, channel access, routing protocols, and privacy and security management. The findings suggest that AI-driven UAV networks are a feasible technological approach for cost-effective deployment in future networks. Success in this domain will require concerted efforts between industry, academia, and government bodies, including telecommunications and regulatory agencies.

Looking ahead, we identify and discuss promising research directions including enhancements in network coverage, access protocols, AI algorithms, and the security and privacy frameworks of UAV networks. New research initiatives are essential to develop effective UAV network architectures and address the numerous design challenges inherent in AI-powered autonomous UAV communication systems. Future works might also explore the integration of AI algorithms for a simpler, sub-optimal solution.

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