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5G and artificial intelligence integration to improve drone routing

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Abstract. The development of 5G and artificial intelligence technologies creates new opportunities for improving the routing of unmanned aerial vehicles, which is particularly relevant for logistics, rescue operations, and monitoring of critical infrastructure. The purpose of the study was to analyse the prospects for implementing 5G and AI in drone routing, identify key challenges, and develop recommendations for their effective integration into Ukrainian airspace. The study used methods of theoretical analysis of scientific sources, comparative analysis of international experience, and systematisation of modern approaches to drone routing using 5G and AI. The architecture of 5G networks, route optimisation algorithms, and coordination mechanisms for swarms of drones was analysed. The main results of the study showed that the combination of 5G and AI provides a significant increase in the efficiency of autonomous unmanned systems, allowing helping to quickly adapt routes, optimise energy consumption, and improve the level of flight safety. Special attention was paid to comparing two popular route optimisation algorithms for UAVs: the particle swarm and the ant colony optimisation algorithms. The analysis showed that both algorithms effectively solve routing problems, but they have their advantages depending on the specifics of the application. The particle swarm algorithm proved to be more efficient for problems with a large number of variables, helping to optimise routes in real time under rapidly changing conditions. The ant colony optimisation algorithm, in turn, demonstrated an advantage in solving complex problems with a large number of obstacles. The practical significance of the study was to identify key technical and regulatory challenges associated with the integration of 5G and AI into drone routing, and to develop evidence-based approaches to solving them. The results obtained can be used to improve national regulations, promote the introduction of intelligent unmanned systems in logistics, infrastructure monitoring and rescue operations, and for further research in the field of autonomous aviation technologies

Keywords: unmanned aerial vehicles; artificial intelligence; blockchain; neural network; drone swarms

INTRODUCTION

The rapidly growing demand for autonomous drone solutions is making the integration of 5G and artificial intelligence (AI) a key area of improvement for their functionality. With 5G capabilities, drones can receive

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and transmit real-time data, which is crucial for coordinating a large number of devices, especially in urban areas or difficult terrain. AI helps to quickly adapt routes, avoiding obstacles and optimising power consumption. As a result, this opens up prospects for creating efficient, safe, and intelligent unmanned systems capable of performing complex tasks with minimal human intervention. Governments and multinational corporations such as the National Aeronautics and Space Administration, the European Aviation Safety Agency, and the International Telecommunications Union are actively developing standards for integrating drones into airspace. Among the key trends in the international arena regarding the integration of 5G and AI in drone routing, the development of autonomous air corridors (U-space in Europe), Unified Traffic Management in the United States) stands out, which provide coordination of drones in the airspace. Major multinational corporations such as Qualcomm, Nokia, and Ericsson are developing Multi-Access Edge Computing technologies to reduce data transfer delays and improve real-time route efficiency.

A literature review showed that research on the integration of AI, unmanned aerial vehicles (UAVs), and 5G networks focuses on optimising communications, security, energy efficiency, and applications in critical areas. According to A. Rovira-Sugranes *et al.* (2022), integrating AI into routing protocols for UAVs can improve efficiency and adaptability in changing network environments. The researchers noted that the main challenges remain optimisation of routes and ensuring the stability of communication in real time. In addition, they concluded that the use of AI allows creating more adaptive and sustainable routes for UAVs, but it is necessary to solve the problem of reducing delays and improving the reliability of communications. This issue was raised by A. Sufyan *et al.* (2023), who analysed 5G networks for UAVs, focusing on regulatory aspects and trends. The researchers noted that ensuring stable communication in conditions of variable radio frequency spectrum and data security requirements is an important challenge. Thus, they concluded that the integration of UAVs into 5G networks opens up new opportunities for applications, but requires improvement of regulatory standards at the international level. Q. Wu *et al.* (2021) supplemented previous research, noting that the development of sensor technologies is crucial for improving communication efficiency and accuracy of data collected by UAVs in 5G networks. According to the researchers, the key aspect is to ensure high-speed communication and accurate data exchange in complex urban environments. Wu *et al.* concluded that 5G networks have great potential for UAV integration, but for effective operation, it is necessary to consider the characteristics of sensor technologies and communications.

The safety and reliability of networks is a critical aspect of UAV development, which was argued by R. Gupta *et al.* (2021), offering blockchain and AI integration to protect drone communications. According to the researchers, the use of blockchain to store records of communications and UAV data provides protection against cyber threats and manipulation. R. Gupta *et al.* emphasised that the combination of blockchain and AI is an effective method for preventing unauthorised access and preserving data integrity in UAV systems. Similar issues were considered by T. Garg *et al.* (2024), who explored the concept of "drones as a service" in smart cities, strengthening data protection through blockchain. They emphasised that this concept is promising for the development of smart city infrastructure. According to researchers, blockchain technologies provide an appropriate level of protection for data transmitted through UAVs within such services. As a result, for the effective implementation of "drones as a service", it is necessary to address data security issues, since this is critical for user trust and system reliability.

Energy efficiency was also an important topic in the context of this study. N. Qasim and A. Jawad (2024) analysed the use of UAVs in 5G networks for efficient energy management. In their opinion, UAVs can become an important tool for optimising energy use, reducing overall costs in 5G infrastructures, which correlates with the findings of P. Majumdar *et al.* (2024). The researchers raised issues of energy efficiency in narrower sectors, in particular, in agriculture, environmental protection, and logistics. According to them, AI-equipped UAVs are capable of performing complex tasks, such as monitoring the state of the environment or making accurate deliveries of goods. Thus, the use of AI in UAVs expands the capabilities of these technologies, making them more efficient and autonomous. However, the development of AI for UAVs was considered in the context of urban infrastructure. A. Warrier *et al.* (2023) noted that AI can be used to reduce interference in urban 5G networks, which is crucial for ensuring uninterrupted communication. According to researchers, the use of AI allows adapting networks to changes in the environment and improving signal stability even in urban interference conditions. Therefore, the introduction of AI in urban 5G networks can significantly improve the quality of communication, ensuring more stable and efficient operation.

Preliminary research on the integration of 5G and AI into drone routing in Ukraine is limited and focuses mainly on individual technical aspects or experimental projects without a systematic analysis of their practical application in the national infrastructure. However, the issues of legal regulation, cybersecurity, and adaptation of world technological standards to the realities of the Ukrainian market have not been sufficiently studied. Given the rapid development of drones for military, logistics, and civilian needs, the purpose of this study was to analyse the prospects for the introduction of 5G and AI in the routing of drones in Ukraine, to identify key challenges for their effective integration into the country's airspace.

MATERIALS AND METHODS

The study was analytical and predictive in nature, combining an overview of modern technological solutions and their potential application in Ukraine. The time frame covered the period 2020-2025, considering the development of 5G infrastructure, the introduction of AI in drone routing, and the adaptation of regulations. Two popular algorithms were used to analyse and optimise drone routes in the study: particle swarm and ant colony algorithms. As part of the study, the effectiveness of these algorithms for solving UAV routing problems in a 5G network was compared. The research was based on the analysis of secondary data obtained by analysing scientific publications, technical documentation, and regulations. The main sources of information were reports from international organisations, such as the International Telecommunications Union (n.d.), International Civil Aviation Organisation (n.d.), and the European Aviation Safety Agency (n.d.), which contain official recommendations and regulatory approaches to the use of 5G and AI in the airspace. In addition, the study covered peer-reviewed research papers published in international journals on unmanned technologies and AI. The analysis of these sources provided a comprehensive understanding of the current state of integration of 5G and AI in drone routing both in the global context and within the Ukrainian market.

To conduct the study, theoretical methods were used that helped to comprehensively analyse the problem. Content analysis was used to systematise scientific, technical, and regulatory sources, which identified key approaches to integrating 5G and AI into unmanned aviation systems. The main areas of research in this area were identified, including technical innovations, regulatory aspects, and development prospects. This allowed assessing the level of readiness of Ukraine to integrate these technologies into the airspace and identifying key barriers, in particular, technical, economic, and legal ones. In addition, a predictive method was used to assess possible scenarios for the development of 5G drones, considering global technological trends, existing infrastructure, and regulatory environment. Thus, it was possible to formulate recommendations on optimal ways to integrate 5G and AI into UAV routing. The integrated use of these methods has enabled a thorough theoretical analysis that contributes to a deeper understanding of the problem and the development of strategic recommendations for the effective use of technologies in the drone industry. The results were interpreted using systematic and comparative approaches, which helped to identify key patterns and differences in the introduction of 5G and AI in drone routing in different countries. Analysing regulatory aspects, technical characteristics, and strategic initiatives, the study used logical generalisation to identify the main trends and challenges. Predictive analysis helped to assess possible scenarios for the development of this technology in Ukraine, based on international experience and available resources.

RESULTS

Intelligent algorithms for routing in drone networks. Intelligent routing algorithms in UAV networks represent a complex interdisciplinary phenomenon that combines machine learning techniques, advanced communication technologies, and principles of decentralised decision-making. Advanced approaches to drone routing use various classes of machine learning algorithms that provide adaptability, predictability, and optimisation of flight paths. One of the fundamental methods is reinforcement learning, in particular Q-learning, which allows autonomous agents to dynamically change route parameters according to the assessment of the environment. The use of deep neural networks contributes to the development of stable models for predicting optimal routes using large amounts of historical and current data. Evolutionary algorithms and neuroevolution, combining genetic mechanisms with neural network architectures, demonstrate high efficiency in adaptive routing scenarios, providing independent adjustment of algorithmic parameters in accordance with environmental changes. Bayesian methods allow modelling probabilistic distributions of possible routes, ensuring a balance between energy efficiency and task completion speed (Trabelsi *et al.*, 2024). The main machine learning algorithms used in drone routing are shown in Table 1.

Table 1. Machine learning algorithms for UAV routing

Algorithm	Description	Advantages	Restrictions
Q-learning	Reinforcement learning, where drones independently adjust routes based on the rewards received for making decisions	Autonomous decision-making, adaptation to changes in the environment	High computational complexity, especially with a large number of possible states
Deep neural networks	Use historical data to predict optimal routes and recognise obstacles	High accuracy, efficiency in complex scenarios	Require large amounts of data for training, high hardware requirements
Evolutionary algorithms	Simulation of natural selection to determine optimal routes based on mutations and crossbreeding	Flexible, fast adaptation to a changing environment	High computing power consumption

Continued Table 1.

Algorithm	Description	Advantages	Restrictions
Neuroevolution-based networks	Combination of neural networks and evolutionary methods for drone self-learning	Automatic optimisation, no need for pre-training	High computing costs, implementation complexity
Bayesian forecasting methods	Use of probabilistic models to predict changes in routes and traffic distribution	High accuracy of forecasts, ability to adapt to noise data	Need for large amounts of statistical data for accurate assessment

Source: compared by the authors based on data analysis by the International Civil Aviation Organisation (n.d.), European Aviation Safety Agency (n.d.)

The use of 5G technology is crucial for improving routing performance in UAV networks, as it provides ultra-low latency, high bandwidth, and resistance to network congestion. High-speed data transmission allows real-time integration of current flight parameters, obstacles, and abnormal environmental changes into the optimal route calculation process. Advanced 5G communication protocols support dynamic distribution of network resources, which is critical for synchronised coordination of large swarm systems. The implementation of Multi-Access Edge Computing also allows transferring computing processes directly to peripheral nodes of the network, providing fast information processing at the level of individual UAVs without having to access remote data centres. This significantly improves the adaptability and responsiveness of decision-making, reducing the risk of delays, which is crucial in a dynamic operating environment (Biswas & Wang, 2023).

Decentralised routing approaches eliminate the problems of centralised management systems that are vulnerable to overloading and node server failures. The use of a blockchain architecture allows for a high degree of security, since each drone acts as a self-sufficient network node, and smart contract algorithms allow automatically adjusting routing in accordance with changing environment parameters. The use of decentralised neural networks allows swarm systems to operate in self-learning mode, allowing each agent to adaptively adjust behaviour based on collective experience. Local data processing using Multi-Access Edge Computing eliminates the need for centralised management, which significantly increases the autonomy and efficiency of resource allocation in swarm structures (Zaid *et al.*, 2024). Thus, the integration of machine learning algorithms, 5G communication capabilities, and decentralised management techniques enables the transformation of network routing systems into UAVs, increasing their adaptability, energy efficiency, and self-learning ability. Further research is expected to further optimise self-organisation mechanisms, develop more efficient methods for reducing energy consumption, and improve the stability of algorithms to variable and adverse operating conditions.

The role of AI in creating dynamic drone networks. AI plays a key role in creating dynamic UAV networks, providing autonomous decision-making, adaptive routing, and optimal interaction between drones. Based on the use of advanced machine learning algorithms, drones can effectively coordinate their actions in real time, process huge amounts of data, and adapt to changing environmental conditions. The integration of 5G technology can significantly improve the efficiency of such networks, providing ultra-low data transfer latency, high bandwidth, and reliable communication, which is critical for dynamic swarm management scenarios (Lins *et al.*, 2021). One of the main challenges in creating dynamic drone networks is the need for fast information processing and collective decision-making without centralised management. The use of deep neural networks allows UAVs to independently analyse the current state of the environment and predict optimal routes. Reinforcement learning allows drones to adjust their trajectory based on accumulated experience, which increases the efficiency of performing tasks in uncertain and dynamic conditions. Such algorithms allow reducing energy costs, minimising the risk of collisions, and providing autonomous strategic decision-making (Alsamhi *et al.*, 2021).

The use of 5G significantly enhances the capabilities of intelligent drone network management systems, as it provides almost instant communication between system elements. In traditional networks, high latency makes it difficult to coordinate actions between UAVs, which can lead to delays in decision-making and loss of efficiency. The implementation of Multi-Access Edge Computing allows processing data on the periphery of the network, which reduces the load on centralised servers and contributes to the rapid response of drones to changes in the environment. This allows using distributed cognitive computing, which enables swarm systems to function more independently and quickly. AI also provides efficient routing of information flows between drones, optimising communication in distributed networks. The use of cognitive radio techniques allows UAVs to independently change communication frequencies depending on the level of interference and channel availability, which minimises the risk of data loss and increases the overall stability of the network. Intelligent spectrum management allows efficient distribution of network resources, reducing congestion of communication channels in areas of high drone activity.

Decentralised routing approaches based on blockchain technologies and distributed computing ensure that the drone network is highly resistant to failures and external attacks. The use of a blockchain architecture guarantees the integrity of the transmitted data, since each drone acts as a node of a decentralised system that verifies the authenticity of information. Smart contracts can automate decisions about route changes by coordinating interaction between UAVs without the need for centralised management. The development of adaptive routing algorithms in the context of drone networks is one of the most promising areas of AI application. The use of evolutionary algorithms and neuroevolution allows developing systems capable of self-learning and improving their strategies over time. Due to the use of genetic algorithms, drone networks can independently choose optimal routes depending on changing environmental parameters, ensuring the most efficient resource allocation (Khan *et al.*, 2021). Special attention should be paid to integrating AI into complex scenarios involving multi-component dynamic environments such as emergencies, large-scale monitoring, and logistics. The use of convolutional neural networks allows automatic processing of visual data, which allows drones to effectively recognise objects, assess risks and make decisions about changing the flight path.

The energy efficiency of drone networks remains a critical issue, which can be solved by optimising AI algorithms. Using deep learning models to predict energy consumption allows allocating resources more efficiently, considering the load factors on battery systems, variable weather conditions, and aerodynamic drag parameters. Based on 5G integration, centralised power management at the level of the entire swarm of drones becomes possible, which allows dynamically redistributing tasks between devices, extending the overall battery life of the system (International Telecommunications Union, n.d.). The prospects for the development of intelligent drone networks are directly related to the improvement of collective learning algorithms, which would allow drones to share knowledge more effectively and adapt to complex scenarios. The use of federated training allows integrating the experience of various autonomous agents into a common model without the need for centralised processing of large amounts of data, which increases the efficiency of the system in highly dynamic conditions. Therefore, the role of AI in creating dynamic drone networks is crucial for achieving a high level of autonomy, efficiency, and adaptability. 5G integration provides a critical infrastructure for high-speed data transmission, enabling scalable swarm management algorithms. In the future, further development of AI will expand the functionality of such systems, ensuring their integration into complex multi-agent environments and increasing the level of autonomy in scenarios with unpredictable changes.

Routing in swarms of drones: collective intelligence. Swarms of drones operating on the basis of the principles of collective intelligence represent a promising area in the development of autonomous systems. Coordinating a large number of UAVs requires efficient routing algorithms to optimise trajectories, minimise energy costs, and avoid collisions. AI and swarm technologies open up new opportunities for autonomous UAV control. The main idea of swarm routing is to create a decentralised system in which drones can coordinate their actions without human intervention. Collective intelligence in such systems works according to the principles of biological swarms, where each element interacts with others to achieve a common goal. This allows for flexibility, adaptability and high resistance to environmental changes.

The use swarm intelligence allows implementing complex collective strategies. For example, an approach based on behavioural models of biological systems allows UAVs to act as a single organism. Moreover, swarm routing algorithms are based on the principles of self-organisation, adaptability, and decentralised decision-making. Many modern routing approaches are based on reproducing natural systems such as flocks of birds, ant colonies, and shoals of fish. These systems demonstrate effective communication and resource allocation strategies without centralised management. In particular, the particle swarm algorithm is an optimisation method based on the behaviour of social groups. Drones are considered "particles" that move in the direction of a globally optimal solution determined through collective analysis of the environment. Each particle updates its speed and position based on personal experience and the experience of its neighbours, which allows the swarm to effectively find optimal routes in difficult conditions (Kourtis *et al.*, 2023). The ant colony algorithm uses principles similar to the behaviour of real ants when searching for food. Virtual pheromones left by drones help to determine the shortest and least congested routes. The more often a particular route is used, the stronger its footprint, which contributes to real-time swarm self-regulation. The considered routing algorithms are presented in Table 2.

Table 2. Comparison of routing algorithms

Algorithm	Operating principle	Advantages	Disadvantages
Particle swarm algorithm	Route optimisation through particle speed and position updates	High convergence rate, adaptability	May get stuck in local optimums

Continued Table 2.

Algorithm	Operating principle	Advantages	Disadvantages
Ant colony algorithm	Using virtual pheromones to find the optimal path	Reliability, efficiency in a dynamic environment	High computing costs

Source: compared by the authors based on the analysis of S.K. Khan (2021)

One of the key advantages of swarm systems is their ability to self-organise. UAVs can jointly determine optimal routes, avoid obstacles, and redistribute tasks among themselves. Machine learning algorithms, neural networks, and reinforcement learning techniques are used for this purpose. Based on this approach, the system can adapt to changing conditions and perform tasks with minimal energy loss. An important component of collective intelligence is the exchange of information between drones. For this purpose, modern communication technologies are used, in particular 5G, which provides fast data transmission with minimal latency. Each UAV in the swarm has up-to-date information about the state of the environment and the actions of other network participants. This allows significantly improving coordination and avoiding conflicts in routing (Dash *et al.*, 2023).

Routing methods in drone swarms can be divided into centralised and decentralised. Centralised approaches involve controlling all drones through a central server or main UAV. They provide high accuracy, but are vulnerable to main element failure. Instead, decentralised methods allow each drone to make its own decisions based on local data, which increases the system's resilience to failures. Deterministic and stochastic algorithms are also distinguished among the key approaches to routing. Deterministic methods are based on strictly defined rules that guarantee predictability of results, but may be less effective in a changing environment. Stochastic methods, by contrast, use probabilistic models that increase their adaptability to dynamic conditions, such as unexpected obstacles or variable weather conditions. For a better visualisation of the main characteristics of these algorithms, a comparative Table 3 is provided.

Table 3. Characteristics of the main routing algorithms

Type of algorithm	Advantages	Disadvantages	Example of application
Deterministic	Predictability, stability	Less adaptability in changing conditions	Flights to the specified coordinates
Stochastic	High flexibility, adaptability to changes	Requires more computing resources	Offline navigation in the face of obstacles

Source: compared by the authors based on the analysis of B. Dash *et al.* (2023)

Due to the use of AI and 5G, swarm algorithms can combine these approaches, automatically switching between deterministic and stochastic methods depending on the situation, which significantly improves the efficiency of flying and controlling swarms of drones. AI significantly expands routing capabilities, giving drones the ability to predict possible threats and change their route in real time. Based on deep learning techniques, UAVs can analyse large amounts of data, recognise objects, and optimise their actions. This is especially important in scenarios that require a quick response, such as rescue operations or military missions. The use of cognitive computing in routing allows drones to adaptively change communication channels depending on the level of interference and frequency availability. Intelligent spectrum management minimises the risk of signal loss and improves overall network stability. This ensures continuous data exchange between swarm elements, even in difficult conditions. A separate area of development is the use of blockchain technologies in swarms of drones (Zaid *et al.*, 2024). They guarantee the protection of transmitted information, since each drone acts as a node of a decentralised network. This significantly increases the security of the system and ensures its resistance to external attacks.

Integration of 5G technology significantly increases the efficiency of swarm routing algorithms, as it provides high-speed information exchange between drones and central computing resources. In conventional networks with high latency, data transmission makes it difficult to synchronise and adapt the swarm to changes in the environment. The use of 5G can significantly reduce these delays due to its low latency (up to 1 ms), which is especially important for highly dynamic scenarios, such as real-time coordination of a large number of drones. In addition, the high bandwidth of 5G allows drones to exchange large amounts of data, including video streams, telemetry, information about obstacles and environmental conditions. Therefore, machine learning algorithms can process current and historical data to better optimise routes and predict possible threats. For example, analysing drone behaviour in the past can help to determine the likelihood of congestion in certain areas or predict the most energy-efficient trajectories.

Another key aspect is the ability to use decentralised data processing models, such as Multi-Access

Edge Computing, which place computing power closer to the task execution location. This reduces reliance on remote data centres and allows swarm drones to make their own decisions without too much delay. As a result, swarm routing becomes more adaptive and efficient, which is important for emergency response, monitoring, and logistics scenarios (Caballero-Martin *et al.*, 2024). Swarms of drones are widely used in various fields due to their autonomy, flexibility and ability to quickly respond to changing conditions. In disaster zones, they can quickly deploy to search for victims, assess damage, and coordinate rescue operations, using 5G connectivity to transmit real-time video streams. In the field of critical infrastructure monitoring, autonomous drones are used to check the state of power grids, bridges, oil and gas pipelines, using Multi-Access Edge Computing for local data processing and deep neural networks for detecting defects. In logistics, swarm routing systems optimise unmanned delivery of goods, using ant algorithms to determine the best routes and minimise energy costs. In agriculture, drones perform spot spraying of fertilisers and pesticides, and monitor the condition of plants using a swarm of particles algorithm to adapt flight paths in accordance with terrain and weather conditions. In smart cities, swarm systems contribute to traffic monitoring, public safety, and environmental control by using deep neural networks to analyse traffic flows, optimise traffic light cycles, and prevent congestion (Sarkar & Gul, 2023). Due to the combination of state-of-the-art AI algorithms and 5G high-speed communication, swarm technologies open up new opportunities for improving efficiency and security in critical areas.

DISCUSSION

The results show that the use of intelligent routing algorithms significantly improves the efficiency and autonomy of drone networks, but their practical implementation faces a number of challenges. In particular, the complexity of adapting algorithms to dynamic real-world conditions and the limitations of UAV computing resources can affect their performance. Although machine learning techniques such as reinforcement learning and neural networks show high flexibility, their implementation requires significant computing power, which can conflict with energy efficiency requirements. Thus, the results highlighted the need to balance performance, energy efficiency, and safety, which opens up prospects for further research in the field of optimising routing algorithms for UAVs. A. Solanki *et al.* (2022) considered the concept of the Internet of drones as a platform for creating intelligent solutions, especially in areas such as monitoring, environmental control, transport and logistics. The book discussed AI algorithms for autonomous drone control that help to improve coordination between UAVs. The main conclusion of the authors was that AI integration allows increasing the efficiency of drone systems in real time. This study also confirmed that AI plays a key role in the future development of the Internet of drones, helping to automate complex tasks in controlling air traffic. However, the problem of energy efficiency is one of the key issues in the use of UAVs. P. Du *et al.* (2023) analysed route optimisation methods for AI-based logistics drones. The researchers proved that properly designed algorithms can reduce energy costs and improve the autonomy of drones. Similar conclusions were drawn by S. Haider *et al.* (2022), who investigated the use of AI for resource management in unmanned networks. They emphasised that the integration of trajectory optimisation and intelligent power management can significantly improve the efficiency of data collection from IoT devices. The theoretical study confirmed these conclusions, focusing on the fact that machine learning algorithms can provide more flexible and adaptive control of drone routes.

In the context of developing hybrid models for UAV routing, it is essential to consider the experience of implementing mobile communication systems for remote drone control. V. Posvistak & D. Miroshnychenko (2024) proposed an architectural model for long-range UAV operation using GSM-based communication modules, combining a ground control station, a mobile router, and a Raspberry Pi computing unit connected to the drone via the MAVLink protocol. The authors emphasised the feasibility of achieving a stable connection even in the absence of line-of-sight between the operator and the UAV, which aligns with key challenges identified in this study regarding the resilience of communication channels in dynamic aerial environments. Another relevant direction for improving UAV navigation and operational security involves the use of machine learning techniques for drone detection and environmental awareness. R. Yermolenko *et al.* (2024) developed a detection algorithm for commercial UAVs based on convolutional neural network architectures such as YOLOv8 and MobileNetV3. Their study demonstrated high accuracy in recognising drones across various visual conditions using the SimUAV dataset, which included diverse drone classes and environments. The authors emphasised that such detection systems are particularly effective in surveillance and monitoring applications, offering real-time identification of aerial threats or system anomalies. These findings align with the broader vision of integrating AI into UAV operations, supporting dynamic route adjustment, adaptive control, and autonomous threat response. When combined with 5G connectivity and edge computing infrastructure, the implementation of intelligent detection algorithms could significantly enhance the resilience and autonomy of UAV networks, especially in high-risk or complex operational scenarios.

The issue of stable communication and data transmission management is critical for the effective functioning of drone networks. T. Ayass *et al.* (2022) and I. Shayea *et al.* (2022) investigated the mechanisms of handover (transmission of communication between base stations) in 5G networks for drones. They found that conventional approaches do not factor in the high mobility of drones, which can lead to loss of communication. An alternative is machine learning-based methods that allow anticipating changes in the network and optimising the transmission process. Similar studies were conducted by M. Khan *et al*. (2022), analysing the use of swarms of drones to manage mobile networks in 6G. They showed that AI-based autonomous routing improves communication between drones and the network, reducing data transfer latency. The conducted research confirmed the relevance of these issues, since the presence of stable communication is a key factor in the successful implementation of unmanned aviation networks in various fields.

The growing use of UAVs also raises safety concerns. F. Tlili *et al*. (2024) examined the use of AI to protect drone networks from cyber-attacks. The researchers emphasised the importance of real-time threat detection and the development of adaptive defence mechanisms. Similarly, T. Han *et al*. (2021) explored the prospects for using blockchain for drones in 5G networks, showing that distributed ledger technologies can provide reliable protection against attacks and unauthorised access. The current paper highlighted the importance of such solutions, although it was noted that scaling blockchain systems in drone networks can be a resource-intensive task. An alternative approach might be to use hybrid models that combine conventional encryption methods and blockchain algorithms. F. Aktas *et al*. (2023) explored the use of AI for routing in next-generation networks. They noted that conventional protocols cannot provide effective communication management in dynamic environments. Similarly, Y. Lu *et al*. (2023) analysed routing algorithms in integrated space-air-ground networks, emphasising the importance of adaptive methods based on deep learning. This study confirmed these findings, emphasising that machine learning algorithms are key to autonomous drone control and optimising data transmission. However, it also focused on potential problems related to the computational complexity of such algorithms.

L. Bine *et al*. (2023) proposed a new IoDMix protocol for integrating drones into intelligent transport systems. They demonstrated that their model allows them to work efficiently in conditions with data transfer delays. B. Mohsen (2024) explored the optimisation of logistics in urban environments using autonomous drones and IoT, confirming the promise of using AI for air traffic control. The paper by B. Mohsen proposed an AI-focused optimisation of urban logistics that combines autonomous vehicles and IoT systems to create efficient delivery systems. The implementation of such solutions can significantly reduce delays caused by urban traffic and optimise the use of energy resources. The study confirmed these results, highlighting the importance of predictive models for controlling large arrays of drones. In addition, A. Hashesh *et al*. (2022) highlighted the challenges and prospects of UAV communication provided by AI technologies. The researchers noted that deep learning and neural networks help drones to adapt to changing conditions, especially in complex urban or combat scenarios. These studies are consistent with theoretical analysis that has shown that IoT and AI can contribute to improving the autonomy of UAVs and their integration into urban and industrial environments. However, challenges related to data security and network sustainability remain open.

One of the key aspects of effective use of drones is the development of routing and network management algorithms that ensure fast and safe movement of UAVs in difficult conditions. The study by M. Khalid *et al*. (2024) revealed the use of AI and machine learning to integrate ground-based and space-based communication networks with UAVs. This integration allows creating multi-level networks that provide a stable connection even in regions with low mobile coverage. The current study confirmed the results of a theoretical analysis that showed that AI algorithms can significantly improve the efficiency of route planning and drone network management. However, the study also identified potential threats related to cybersecurity and the risks of interference in autonomous systems, which requires further research. Thus, the study confirmed that AI algorithms significantly improve routing, reduce latency, and increase the safety of drones in difficult environments. However, a number of challenges remain, in particular ensuring stable communications, cybersecurity, and energy efficiency.

CONCLUSIONS

The results provide a deeper understanding of adaptive routing mechanisms, which are essential for improving the efficiency and autonomy of unmanned networks. The results of the analysis contributed to the goal of the study, as they revealed gaps in regulation, technical support, and strategies for integrating 5G and AI into drone routing. This, in turn, contributed to the development of a safe and efficient drone infrastructure that can be used in logistics, infrastructure monitoring, defence, and smart cities. Machine learning algorithms such as Q-learning, deep neural networks, and evolutionary approaches have been found to optimise drones' flight routes, increasing their autonomy and ability to adapt in a dynamic environment. The use of 5G technology can significantly improve the speed of data processing and coordination of swarm systems, while Multi-Access Edge Computing minimises latency and promotes local data processing.

The role of AI in creating dynamic drone networks that ensure fast decision-making, efficient routing, and optimal resource allocation was investigated. The use of decentralised methods, such as blockchain and cognitive radio, increases the resilience of networks to external threats and provides reliable communication between system agents. In particular, swarm routing methods, created based on biological systems, such as ant colonies or flocks of birds, provide flexibility, self-organisation, and adaptability for a swarm of drones to environmental changes. The use of particle swarm and ant colony algorithms allows optimising routing, considering energy costs, interference, and task priority. Swarms of drones are widely used in various fields due to their autonomy, flexibility and ability to quickly respond to changing conditions. In disaster zones, they can quickly deploy to search for victims, assess damage, and coordinate rescue operations, using 5G connectivity to transmit real-time video streams. In the field of critical infrastructure monitoring, autonomous drones are used to check the state of power grids, bridges, oil and gas pipelines, using Multi-Access Edge Computing for local data processing and deep neural networks for detecting defects.

The practical significance of the results obtained lies in the implementation of efficient routing algorithms that can be used for logistics tasks, environmental monitoring, rescue operations, and military applications. The results may be useful for developers of autonomous UAV control systems, drone network operators, and AI researchers. Further research should be aimed at optimising self-organisation mechanisms, improving the energy efficiency of drones and expanding the possibilities of their interaction in complex multi-agent environments. Special attention should be paid to the use of cognitive computing and 5G in combination with machine learning technologies to ensure rapid adaptation of the swarm to changing conditions and increase the level of autonomy of unmanned systems.

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REFERENCES

[1] Aktas, F., Shayea, I., Ergen, M., & El-Saleh, A.A. (2023). Ai-enabled routing in next-gen networks: A brief overview. In *Proceedings of the 10th international conference on wireless networks and mobile communications* (pp. 1-6). Istanbul: IEEE. doi: 10.1109/WINCOM59760.2023.10322945.

[2] Alsamhi, S.H., Afghah, F., Sahal, R., Hawbani, A., Al-qaness, M.A., Lee, B., & Guizani, M. (2021). Green internet of things using UAVs in B5G networks: A review of applications and strategies. *Ad Hoc Networks*, 117, article number 102505. doi: 10.1016/j.adhoc.2021.102505.

[3] Ayass, T., Coqueiro, T., Carvalho, T., Jailton, J., Araújo, J., & Francês, R. (2022). Unmanned aerial vehicle with handover management fuzzy system for 5G networks: Challenges and perspectives. *Intelligence & Robotics*, 2(1), 20-36. doi: 10.20517/ir.2021.07.

[4] Bine, L.M., Boukerche, A., Ruiz, L.B., & Loureiro, A.A. (2023). IoDMix: A novel routing protocol for delay-tolerant internet of drones integration in intelligent transportation system. *Ad Hoc Networks*, 148, article number 103204. doi: 10.1016/j.adhoc.2023.103204.

[5] Biswas, A., & Wang, H.C. (2023). Autonomous vehicles enabled by the integration of IoT, edge intelligence, 5G, and blockchain. *Sensors*, 23(4), article number 1963. doi: 10.3390/s23041963.

[6] Caballero-Martin, D., Lopez-Guede, J.M., Estevez, J., & Graña, M. (2024). Artificial intelligence applied to drone control: A state of the art. *Drones*, 8(7), article number 296. doi: 10.3390/drones8070296.

[7] Dash, B., Ansari, M.F., & Swayamsiddha, S. (2023). Fusion of artificial intelligence and 5G in defining future UAV technologies – a review. In *Proceedings of the international conference on device intelligence, computing and communication technologies* (pp. 312-316). Dehradun: IEEE. doi: 10.1109/DICCT56244.2023.10110231.

[8] Du, P., He, X., Cao, H., Garg, S., Kaddoum, G., & Hassan, M.M. (2023). AI-based energy-efficient path planning of multiple logistics UAVs in intelligent transportation systems. *Computer Communications*, 207, 46-55. doi: 10.1016/j.comcom.2023.04.032.

[9] European Aviation Safety Agency. (n.d.). *Aviation safety reporting*. Retrieved from https://www.easa.europa.eu/en/domains/safety-management/aviation-safety-reporting.

[10] Garg, T., Gupta, S., Obaidat, M.S., & Raj, M. (2024). Drones as a service (DaaS) for 5G networks and blockchain-assisted IoT-based smart city infrastructure. *Cluster Computing*, 27, 8725-8788. doi: 10.1007/s10586-024-04354-1.

[11] Gupta, R., Kumari, A., & Tanwar, S. (2021). Fusion of blockchain and artificial intelligence for secure drone networking underlying 5G communications. *Transactions on Emerging Telecommunications Technologies*, 32(1), article number e4176. doi: 10.1002/ett.4176.

[12] Haider, S.A., Zikria, Y.B., Garg, S., Ahmad, S., Hassan, M.M., & AlQahtani, S.A. (2022). Ai-based energy-efficient UAV-assisted IoT data collection with integrated trajectory and resource optimization. *IEEE Wireless Communications*, 29(6), 30-36. doi: 10.1109/MWC.001.2200105.

[13] Han, T., Ribeiro, I.D., Magaia, N., Preto, J., Segundo, A.H., De Macedo, A.R., Muhammad, K., & De Albuquerque, V.H. (2021). Emerging drone trends for blockchain-based 5G networks: Open issues and future perspectives. *IEEE Network*, 35(1), 38-43. doi: 10.1109/MNET.011.2000151.

[14] Hashesh, A.O., Hashima, S., Zaki, R.M., Fouda, M.M., Hatano, K., & Eldien, A.S. (2022). AI-enabled UAV communications: Challenges and future directions. *IEEE Access*, 10, 92048-92066. doi: 10.1109/ACCESS.2022.3202956.
[15] International Civil Aviation Organization. (n.d.). *Safety reports*. Retrieved from https://www.icao.int/safety/pages/safety-report.aspx.
[16] International Telecommunication Union. (n.d.). *Latest reports and publications*. Retrieved from https://www.itu.int/en/action/environment-and-climate-change/Pages/latest-reports-and-publications.aspx.
[17] Khalid, M., Ali, J., & Roh, B.H. (2024). Artificial intelligence and machine learning technologies for integration of terrestrial in non-terrestrial networks. *IEEE Internet of Things Magazine*, 7(1), 28-33. doi: 10.1109/IOTM.001.2300190.
[18] Khan, M.A., Kumar, N., Mohsan, S.A., Khan, W.U., Nasralla, M.M., Alsharif, M.H., Żywiołek, J., & Ullah, I. (2022). Swarm of UAVs for network management in 6G: A technical review. *IEEE Transactions on Network and Service Management*, 20(1), 741-761. doi: 10.1109/TNSM.2022.3213370.
[19] Khan, S.K., Naseem, U., Siraj, H., Razzak, I., & Imran, M. (2021). The role of unmanned aerial vehicles and mmWave in 5G: Recent advances and challenges. *Transactions on Emerging Telecommunications Technologies*, 32(7), article number e4241. doi: 10.1002/ett.4241.
[20] Kourtis, M.A., Xilouris, G., Oikonomakis, A., Batistatos, M.C., & Chochliouros, I. (2023). Integration of drone connectivity in 5G: An examination of the OASEES framework. In *Proceedings of the IEEE future networks world forum* (pp. 1-6). Baltimore: IEEE. doi: 10.1109/FNWF58287.2023.10520379.
[21] Lins, S., Cardoso, K.V., Both, C.B., Mendes, L., De Rezende, J.F., Silveira, A., Linder, N., & Klautau, A. (2021). Artificial intelligence for enhanced mobility and 5G connectivity in UAV-based critical missions. *IEEE Access*, 9, 111792-111801. doi: 10.1109/ACCESS.2021.3103041.
[22] Lu, Y., Wen, W., Igorevich, K.K., Ren, P., Zhang, H., Duan, Y., Zhu, H., & Zhang, P. (2023). UAV ad hoc network routing algorithms in space-air-ground integrated networks: Challenges and directions. *Drones*, 7(7), article number 448. doi: 10.3390/drones7070448.
[23] Majumdar, P., Mitra, S., Bhattacharya, D., & Bhushan, B. (2024). Enhancing sustainable 5G powered agriculture 4.0: Summary of low power connectivity, internet of UAV things, AI solutions and research trends. *Multimedia Tools and Applications*. doi: 10.1007/s11042-024-19728-1.
[24] Mohsen, B.M. (2024). Ai-driven optimization of urban logistics in smart cities: Integrating autonomous vehicles and IoT for efficient delivery systems. *Sustainability*, 16(24), article number 11265. doi: 10.3390/su162411265.
[25] Posvistak, V., & Miroshnychenko, D. (2024). Usage of mobile network for remote drone. *Technologies and Engineering*, 25(4), 73-84. doi: 10.30857/2786-5371.2024.4.7.
[26] Qasim, N.H., & Jawad, A.M. (2024). 5G-enabled UAVs for energy-efficient opportunistic networking. *Heliyon*, 10(12), article number e32660. doi: 10.1016/j.heliyon.2024.e32660.
[27] Rovira-Sugranes, A., Razi, A., Afghah, F., & Chakareski, J. (2022). A review of AI-enabled routing protocols for UAV networks: Trends, challenges, and future outlook. *Ad Hoc Networks*, 130, article number 102790. doi: 10.1016/j.adhoc.2022.102790.
[28] Sarkar, N.I., & Gul, S. (2023). Artificial intelligence-based autonomous UAV networks: A survey. *Drones*, 7(5), article number 322. doi: 10.3390/drones7050322.
[29] Shayea, I., Dushi, P., Banafaa, M., Rashid, R.A., Ali, S., Sarijari, M.A., Daradkeh, Y.I., & Mohamad, H. (2022). Handover management for drones in future mobile networks – a survey. Sensors, 22(17), article number 6424. doi: 10.3390/s22176424.
[30] Solanki, A., Tarar, S., Singh, S.P., & Tayal, A. (2022). *The internet of drones: AI applications for smart solutions*. London: CRC Press.
[31] Sufyan, A., Khan, K.B., Khashan, O.A., Mir, T., & Mir, U. (2023). From 5G to beyond 5G: A comprehensive survey of wireless network evolution, challenges, and promising technologies. *Electronics*, 12(10), article number 2200. doi: 10.3390/electronics12102200.
[32] Tlili, F., Ayed, S., & Fourati, L.C. (2024). Advancing UAV security with artificial intelligence: A comprehensive survey of techniques and future directions. *Internet of Things*, 27, article number 101281. doi: 10.1016/j.iot.2024.101281.
[33] Trabelsi, N., Fourati, L.C., & Chen, C.S. (2024). Interference management in 5G and beyond networks: A comprehensive survey. *Computer Networks*, 239, article number 110159. doi: 10.1016/j.comnet.2023.110159.
[34] Warrier, A., Al-Rubaye, S., Inalhan, G., & Tsourdos, A. (2023). AI-enabled interference mitigation for autonomous aerial vehicles in urban 5G networks. *Aerospace*, 10(10), article number 884. doi: 10.3390/aerospace10100884.
[35] Wu, Q., Xu, J., Zeng, Y., Ng, D.W., Al-Dhahir, N., Schober, R., & Swindlehurst, A.L. (2021). A comprehensive overview on 5G-and-beyond networks with UAVs: From communications to sensing and intelligence. *IEEE Journal on Selected Areas in Communications*, 39(10), 2912-2945. doi: 10.1109/JSAC.2021.3088681.

[36] Yermolenko, R., Klekots, D., & Gogota, O. (2024). Development of an algorithm for detecting commercial unmanned aerial vehicles using machine learning methods. *Machinery & Energetics,* 15(2), 33-45. doi: 10.31548/machinery/2.2024.33.
[37] Zaid, M., Kadir, M.K., Shayea, I., & Mansor, Z. (2024). Machine learning-based approaches for handover decision of cellular-connected drones in future networks: A comprehensive review. *Engineering Science and Technology, an International Journal*, 55, article number 101732. doi: 10.1016/j.jestch.2024.101732.

Інтеграція 5G та штучного інтелекту для вдосконалення маршрутизації у дронах

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Анотація. Розвиток технологій 5G та штучного інтелекту створює нові можливості для вдосконалення маршрутизації безпілотних літальних апаратів, що є особливо актуальним для логістики, рятувальних операцій та моніторингу критичної інфраструктури. Метою дослідження був аналіз перспектив впровадження 5G та AI у маршрутизацію дронів, визначення ключових викликів та розробка рекомендацій для їх ефективної інтеграції у повітряний простір України. У дослідженні використано методи теоретичного аналізу наукових джерел, порівняльного аналізу міжнародного досвіду та систематизації сучасних підходів до маршрутизації дронів із використанням 5G і AI. Проведено аналіз архітектури 5G-мереж, алгоритмів оптимізації маршрутів та механізмів координації роїв дронів. Основні результати дослідження продемонстрували, що поєднання 5G та AI забезпечує значне підвищення ефективності автономних безпілотних систем, дозволяючи оперативно адаптувати маршрути, оптимізувати енергоспоживання та підвищувати рівень безпеки польотів. Особлива увага в дослідженні приділена порівнянню двох популярних алгоритмів оптимізації маршрутів для БПЛА: алгоритм рою часток та мурашиний алгоритм. Аналіз показав, що обидва алгоритми ефективно вирішують завдання маршрутизації, однак мають свої переваги в залежності від специфіки застосування. Алгоритм рою часток виявився більш ефективним для задач з великою кількістю змінних, дозволяючи оптимізувати маршрути в реальному часі при швидко змінюваних умовах. Мурашиний алгоритм, в свою чергу, продемонстрував перевагу у вирішенні складних задач з великою кількістю перешкод. Практичне значення дослідження полягає у визначенні ключових технічних і регуляторних викликів, пов'язаних з інтеграцією 5G та AI у маршрутизацію дронів, а також у розробці науково обґрунтованих підходів до їх вирішення. Отримані результати можуть бути використані для вдосконалення національних нормативних актів, сприяння впровадженню інтелектуальних безпілотних систем у сферах логістики, моніторингу інфраструктури та рятувальних операцій, а також для подальших досліджень у галузі автономних авіаційних технологій

Ключові слова: безпілотні літальні апарати; штучний інтелект; блокчейн; нейромережа; рої дронів