

FLYING AD-HOC NETWORKS: REVIEW, CHALLENGES, ARCHITECTURE, PROTOCOLS, COMMUNICATION AND MODELING

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Abstract: This paper examines one of the most promising areas in the development of wireless self-organizing networks: FANETs, which are based on unmanned aerial vehicles (UAVs). The article explores various issues and unresolved problems related to communication organization within FANET networks. It provides an overview of existing protocols across different layers, including the physical layer, media access control, network layer, and transport layer. While single UAV systems have been used for decades, there are many advantages to using a group of small UAVs instead of relying on a single large UAV. However, multi-UAV aerial systems come with their own challenges, and one of the most significant design challenges is communication. This paper considers the Flying Ad-Hoc Network (FANET) as a new network category, primarily an ad hoc network for UAVs.

Keywords: FANET, VANET, MANET, UAV, architecture, protocol, modeling.

UCHUVCHI AD-HOC TARMOQLARI: UMUMIY TAHLIL, MUAMMOLAR, ARXITEKTURA, PROTOKOLLAR, ALOQA VA MODELLASHTIRISH

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Annotatsiya: Ushbu maqolada simsiz oʻzini oʻzi tashkil qiluvchi tarmoqlarni rivojlantirishning eng istiqbolli yoʻnalishlaridan biri koʻrib chiqiladi: FANETlar, ular uchuvchisiz uchish apparatlari (UUA) ga asoslangan. Maqolada FANET tarmoqlarida aloqani tashkil qilish bilan bogʻliq turli muammolar va hal etilmagan masalalar koʻrib chiqiladi. U turli pogʻonalar, jumladan, fizik pogʻona, kanal pogʻonasi, tarmoq pogʻonasi va transport pogʻonasi boʻyicha mavjud protokollar haqida umumiy maʼlumot beriladi. Yagona UUA tizimlari oʻnlab yillar davomida qoʻllanilgan boʻlsa-

da, bitta katta UUAg tayanish o'rniga kichik UUAlar guruhidan foydalanishning ko'plab afzalliklari bor. Biroq, ko'p uchuvchisiz uchish vositalari o'z muammolari bilan birga kelmoqda va loyihalashdagi eng muhim muammolardan biri aloqadir. Ushbu maqolada Flying Ad-Hoc Network (FANET) yangi tarmoq toifasi, birinchi navbatda UUAlar uchun maxsus tarmoq sifatida ko'rib chiqiladi.

Kalit so'zlar: *FANET, VANET, MANET, UUA, arxitektura, protokol, modellash*.

ЛЕТАЮЩИЕ СПЕЦИАЛЬНЫЕ СЕТИ: ОБЗОР, ПРОБЛЕМЫ, АРХИТЕКТУРА, ПРОТОКОЛЫ, СВЯЗЬ И МОДЕЛИРОВАНИЕ

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Аннотация: В данной статье рассматривается одно из самых перспективных направлений в разработке беспроводных самоорганизующихся сетей: FANET, которые основаны на беспилотных летательных аппаратах (БПЛА). В статье рассматриваются различные вопросы и нерешенные проблемы, связанные с организацией связи в сетях FANET. В ней дается обзор существующих протоколов на разных уровнях, включая физический уровень, управление доступом к среде, сетевой уровень и транспортный уровень. Хотя системы с одним БПЛА использовались десятилетиями, существует множество преимуществ в использовании группы небольших БПЛА вместо того, чтобы полагаться на один большой БПЛА. Однако воздушные системы с несколькими БПЛА имеют свои собственные проблемы, и одной из самых значительных проблем проектирования является связь. В данной статье рассматривается летающая специальная сеть (FANET) как новая категория сетей, в первую очередь специальная сеть для БПЛА.

Ключевые слова: *FANET, VANET, MANET, БПЛА, архитектура, протокол, моделирование*

INTRODUCTION

Rapid technological advances in electronics, sensors, and communication technologies have enabled the creation of unmanned aerial vehicles (UAVs) that can fly autonomously or be remotely controlled without human intervention. Due to their

versatility, flexibility, ease of installation, and relatively low operating costs, UAVs are used in both military and civilian applications such as search and destroy operations¹, border control², and forest firefighting³. They also open up new opportunities for battle⁴, relays for peer-to-peer networks^{5,6}, wind estimation⁷, natural disaster monitoring⁸, remote sensing⁹, and traffic monitoring¹⁰.

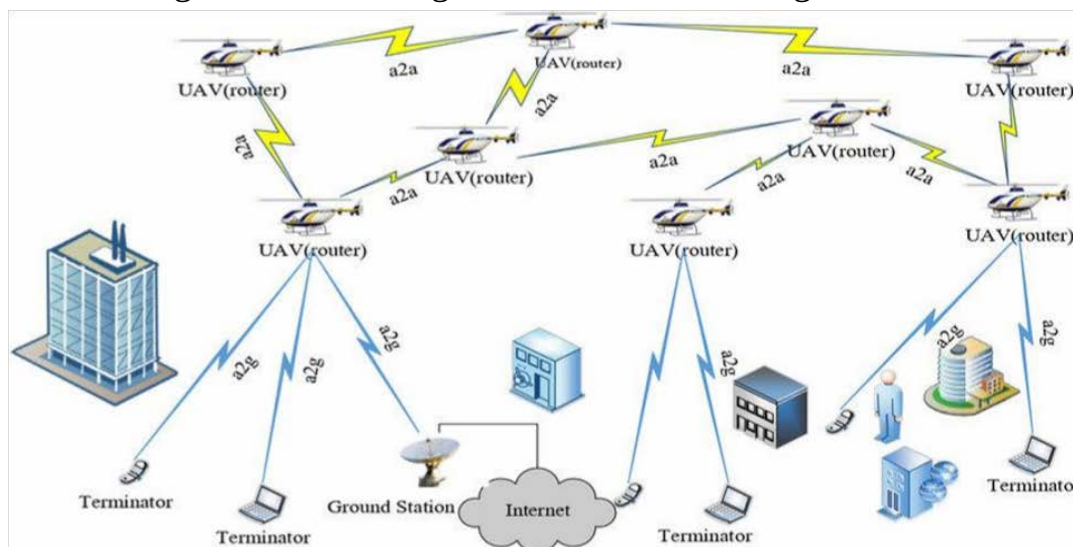


Figure - 1. FANETS

Although single UAV systems have been used for decades, there are many advantages to using a group of small UAVs instead of developing and operating a single large UAV. However, many UAV systems also face unique challenges, with communication being one of the most significant design issues. This paper considers the Flying Ad Hoc Network (FANET), which is essentially a peer-to-peer network among UAVs, as a new category of networks. The differences between mobile ad hoc

¹ Zafar, Wajiya, and Bilal Muhammad Khan. "A reliable, delay bounded and less complex communication protocol for multicluster FANETs." *Digital Communications and Networks* 3, no. 1 (2017): 30-38

² Khan, Ali, Farooq Aftab, and Zhongshan Zhang. "Self-organization-based clustering scheme for FANETs using Glowworm Swarm Optimization" *Physical Communication* 36 (2019): 100769

³ You, Wenjing, Chao Dong, Xiao Cheng, Xiaojun Zhu, Qihui Wu, and Guihai Chen. "Joint optimization of area coverage and mobile-edge computing with clustering for FANETs." *IEEE Internet of Things Journal* 8, no. 2 (2020): 695-707

⁴ AlKhatieb, Anas, Emad Felemban, and Atif Naseer. "Performance evaluation of ad-hoc routing protocols in (FANETs)" In *2020 IEEE wireless communications and networking conference workshops (WCNCW)*, pp. 1-6. IEEE, 2020

⁵ Sang, Qianqian, Honghai Wu, Ling Xing, Huahong Ma, and Ping Xie. "An energy-efficient opportunistic routing protocol based on trajectory prediction for FANETs." *IEEE Access* 8 (2020): 192009-192020

⁶ Da Cruz, E.P.F. "A comprehensive survey in towards to future FANETs" *IEEE Latin America Transactions* 16, no.3 (2018): 876-884. [7] [9] Bekmezci, İlker, Eren Şentürk, and Tolgahan Türker. "Security issues in flying ad-hoc networks (FANETS)." *Journal of Aeronautics and Space Technologies* 9, no. 2 (2016): 13-21

⁷ C. Barrado, R. Messeguer, J. Lopez, E. Pastor, E. Santamaria and P. Royo, "Wildfire monitoring using a mixed air-ground mobile network," *IEEE Pervasive Computing* 9 (4) (2010), pp. 24-32

⁸ E.P. de Freitas, T. Heimfarth, I.F. Netto, C.E. Lino, C.E. Pereira, A.M. Ferreira, F.R. Wagner and T. Larsson, "UAV relay network to support WSN connectivity," *ICUMT, IEEE*, 2010, pp. 309-314

⁹ Bekmezci, O. K. Sahingoz, and S. Temel, "Flying ad-hoc networks (FANETs): A survey," *Ad Hoc Networks* vol. 11, no. 3, pp. 1254-1270, 2013

¹⁰ Gupta, R. Jain, and G. Vaszun, "Survey of important issues in UAV communication networks," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1123-1152, 2015

networks (MANETs), vehicular ad hoc networks (VANETs), and FANETs are described, and the most important design issues for FANETs are presented. In addition to existing solutions, open research questions are also discussed.

FANETs: FANETs are ad hoc networks specifically designed for communication between UAVs, as shown in Figure 1. The challenges faced by FANETs are significant due to the 3D maneuverability of unmanned aerial vehicles and the need to account for obstacles, varying heights, and air traffic rules⁷. Efficient network architectures, routing protocols, collision avoidance mechanisms, and secure communication are among the critical design challenges faced by FANETs.

RELATED WORK

Along with the development of embedded systems and the trend toward miniaturization of microelectromechanical systems, small or mini UAVs can be produced at low cost. However, the capabilities of a single small UAV are limited. Coordinating and cooperating with multiple UAVs can create a system that exceeds the capabilities of a single UAV alone. The advantages of multi-UAV systems can be summarized as follows:

Cost: The cost of purchasing and maintaining small UAVs is significantly lower than that of large UAVs¹⁰.

Scalability: While a single large UAV provides limited coverage area¹¹, a system of multiple small UAVs can easily scale up operations.

Survivability: If a single UAV fails during a mission, the mission cannot continue. However, in a multi-UAV system, other UAVs can continue the operation even if one fails.

Acceleration: Missions can be completed more quickly with a larger number of UAVs¹².

Radar Signature: Instead of a single large radar cross section, multiple small UAVs produce very small radar cross sections, which is particularly advantageous for military applications¹³.

Although multi-UAV systems offer several advantages, they face unique challenges compared to single UAV systems, particularly in communication. In a single UAV system, communication typically occurs via a ground base or satellite, with a single connection established between the UAV and the infrastructure. However, as the number of UAVs increases in multi-UAV systems, developing an effective network architecture becomes a critical issue.

¹¹ Oubbati, O.S.; Atiquzzaman, M.; Lorenz, P.; Tareque, H.; Hossain S. Routing in Flying Ad Hoc Networks: Survey, Constraints, and Future Challenge Perspectives. *IEEE Access* 2019, 7, 81057–81105.3

¹² Bujari, A.; Calafate, C.T.; Cano, J.C.; Manzoni, P.; Palazzi, C.E.; Ronzani, D. Flying ad-hoc network application scenarios and mobility models. *Int. J. Distrib. Sens. Networks* 2017, 13, 10

¹³ Parihar A.S., Chakraborty S.K. Flying Ad Hoc Network (FANET): Opportunities, Trending Applications and Simulators // 2022 IEEE Pune Section International Conference (PuneCon)

In a multi-UAV system, UAVs can also be linked to a ground base or satellite. Solutions based on star topology¹⁴ are one approach, where some UAVs communicate with a ground base, while others connect to satellites. In this setup, communication between UAVs still relies on infrastructure. This infrastructure-based approach has several design challenges:

Cost and Complexity: Each UAV must be equipped with expensive and complex equipment to communicate with a ground base or satellite.

Communication Reliability: Dynamic environmental conditions, node movement, and terrain can disrupt communication.

Range Limitation: UAVs outside the coverage area of the ground base may become unable to communicate effectively.

An alternative solution for multi-UAV systems is the creation of a specialized inter-UAV network called a Flying Ad Hoc Network (FANET). In this approach, even if some UAVs can communicate with a ground base or satellite, all UAVs form a dedicated network among themselves. This allows UAVs to communicate directly with each other and with the ground base, enhancing overall communication effectiveness and flexibility.

COMPARISON BETWEEN FANETS AND MANETS' OTHER TYPES

FANETs can be considered a specialized form of MANET and VANET, but there are distinct differences between FANET and existing peer-to-peer networks:

Mobility: The degree of mobility of FANET nodes is significantly higher than that of MANET or VANET nodes. While conventional MANET and VANET nodes are typically driven by humans and machines, respectively, FANET nodes are airborne.

Topology Changes: Due to the high mobility of FANET nodes, their network topology changes more frequently compared to the relatively stable topologies of MANET and VANET networks.

Communication and Data Collection: Like existing special networks, FANET requires peer-to-peer connections for UAV coordination and cooperation. Additionally, FANET often collects environmental data and transmits it to a control center, similar to wireless sensor networks¹⁵. Therefore, FANET must support both peer-to-peer communication and data aggregation.

Communication Range: The typical distances between nodes in FANETs are much larger than those in MANETs and VANETs¹⁶. For UAV communication, the

¹⁴ Tropea, Mauro; Fazio, Peppino; De Rango, Floriano; Cordeschi, Nicola. (2020). A New FANET Simulator for Managing Drone Networks and Providing Dynamic Connectivity. *Electronics*, 9(4), 543

¹⁵ Shirmohammadi, Shahin S., Ali Al-Hammadi, and Khaled B. Letaief. "Flying Ad-Hoc Networks (FANETs): A Survey." *IEEE Access* 8 (2020): 101234-101248

¹⁶ Zhang, Y., L. Xie, Y. Zhang, and W. Zhang. "Flying Ad-Hoc Networks: A Review." *Journal of Communications and Networks* 24, no. 5 (2022): 475-493

communication range needs to be greater, impacting radio communications, hardware circuits, and physical layer behaviors.

Sensor Data Delivery: Many UAV systems include various types of sensors, each of which may require different data delivery strategies.

Definition and Classification: FANET nodes can be defined as a specific type of MANET where the nodes are UAVs. According to this definition, a system with a single UAV does not constitute a FANET; it requires multiple UAVs to form one. Additionally, not all multi-UAV systems qualify as FANETs. To be classified as a FANET, UAV communication must be conducted using a dedicated network between UAVs. If UAV-UAV communication relies solely on UAV-infrastructure communication, it cannot be classified as a FANET.

In the literature, studies related to FANET are often categorized under different names. For instance, a swarm of aerial robots refers to a joint and autonomous system of multiple UAVs, typically with a specialized network architecture¹⁷. In this context, dedicated aerial robot teams can also be considered FANET projects. However, research on aerial robot teams has primarily concentrated on the cooperative coordination of UAVs rather than on network structures, algorithms, or protocols¹⁸.

Another related topic is the air sensor network^{19,20,21}. An aerial sensor network is a highly specialized mobile network where the nodes are UAVs equipped with sensors. These networks move through the environment, collect data using the UAVs' sensors, and transmit this data to a ground base. In addition, UAVs can act autonomously to achieve specific missions. The distinction between referring to this as a "Flying Ad Hoc Network" or an "Airborne Sensor Network" is more about terminology. Traditional sensor networks focus on issues like power consumption and node density²², which are less relevant for multi-UAV systems. UAVs typically have sufficient energy to support their communication equipment, and the node density in a multi-UAV system is relatively low compared to traditional sensor networks. Therefore, it is more appropriate to classify a multi-role UAV communication system based on inter-UAV communication links as an ad hoc network rather than an ad hoc sensor network.

¹⁷Shahzadi, Anam, Huma M. S., and Imran Ashraf. "A Survey of Protocols and Challenges in FANETs." *Ad Hoc Networks* 98 (2021): 102052

¹⁸Khan, M. F. U., H. Hussain, and M. F. Shamsi. "Challenges and Opportunities in FANETs for Disaster Management." *IEEE Access* 9 (2021): 12256-12268

¹⁹Mak, T. W. K., K. C. Lee, and H. A. Chan. "FANET: A Review of Flying Ad-Hoc Networks." *IEEE International Conference on Communications (ICC)*, 2020: 1-6

²⁰Ren, Y., and L. Wang. "Mobility Management and Communication Protocols for FANETs." *IEEE International Conference on Mobile Ad-Hoc and Sensor Systems (MASS)*, 2021: 345-350

²¹Hussein, M. R. Z. "Flying Ad-Hoc Networks: Protocol Design and Analysis." PhD Dissertation, University of California, Berkeley, 2020

²²Shahzad, A. "Design and Modeling of FANETs for Real-Time Communication." Master's Thesis, University of Edinburgh, 2019

The term “UAV Ad Hoc Network”²³ is closely related to FANET. In fact, there is no significant difference between the existing research on UAV ad hoc networks and the definition of FANET. However, the term FANET emphasizes its nature as a specialized form of MANET and VANET. For this reason, we prefer to use the term “Flying Ad-Hoc Network” (FANET).

Wireless ad hoc networks are categorized based on usage, deployment, communication, and functions. FANET is a subset of MANET, and there are many shared design considerations between MANET and FANET. Additionally, FANET can also be classified as a subset of VANET, which is in turn a subset of MANET. This relationship is illustrated in Figure 2.

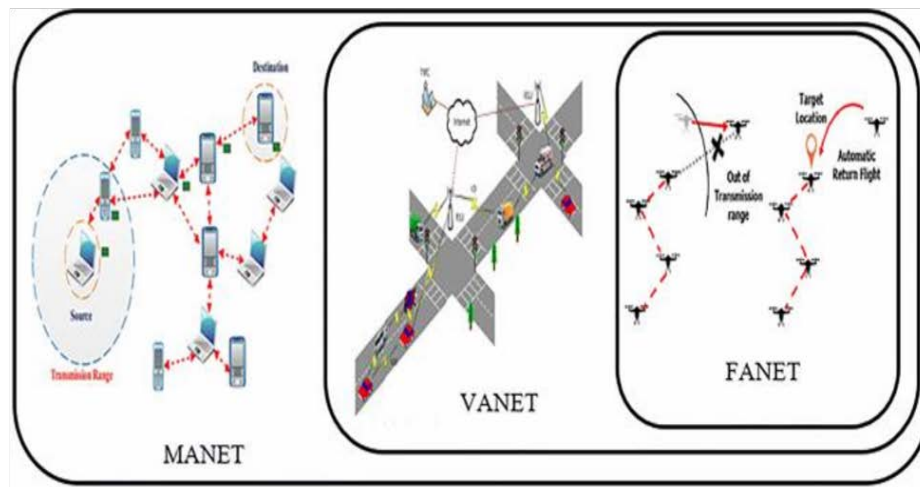


Figure - 2. MANET, VANET AND FANET

As an emerging research area, FANET shares common features with MANET and VANET but also presents several unique design challenges. This subsection provides a detailed explanation of the differences between FANETs and existing wireless ad hoc networks. Table 1 summarizes these differences across the three categories of specialized networks.

MANET nodes move within a certain area, VANET nodes travel along highways, and FANET nodes fly in the sky. MANETs typically use a random waypoint mobility model²⁴, where node directions and speeds are chosen randomly. In contrast, VANET nodes, restricted to highways or roads, exhibit highly predictable mobility patterns.

In some multiple UAV applications, global route plans are preferred, leading UAVs to follow specific trajectories with a regular mobility model. However, in autonomous systems with multiple UAVs, the flight plan is not always predetermined. While many UAV systems use predefined flight plans, environmental changes or

²³Bhatia, A. K. S., A. M. Boudy, and A. P. Sharma. "Flying Ad-Hoc Networks (FANETs): A Review and Future Directions." ResearchGate, 2021. <https://www.researchgate.net/publication/333681900>

²⁴Shirmohammadi, Shahin, and Mohammad R. Alarifi. "Flying Ad-Hoc Networks: Challenges and Protocols." arXiv Preprint 2204.01713 (2022)

mission updates can necessitate recalculating the flight plan. Additionally, rapid and abrupt UAV movements, coupled with varying UAV structures, directly influence the mobility patterns of many UAV systems. To address these challenges, various FANET mobility models have been proposed.

While the random mobility model is straightforward, it may lead to suboptimal route plans for cooperative UAV applications. Conversely, the pheromone-based model offers more reliable scanning properties and improved performance.

Nodal density is defined as the average number of nodes per unit area. FANET nodes are typically dispersed across the sky, and even within small multi-UAV systems, the distance between UAVs can be several kilometers²⁵. Consequently, FANET has a much lower node density compared to MANET and VANET.

Table 1

The comparison of MANET, VANET and FANET

<i>Types parameters</i>	<i>Types of Ad-Hoc Networks</i>		
	<i>MANET</i>	<i>VANET</i>	<i>FANET</i>
Node mobility	Low	High	Very high
Mobility model	Random	Regular	Regular for predetermined
Node density	Low	High	Very low
Topology change	Slow	Fast	Fast
Radio propagation model	Close to ground	Close to ground	High above the ground
Power consumption, network lifetime	Energy efficient protocols	Not needed	Energy efficiency for mini UAV, but not needed
Computational power	Limited	High	High
Localization	GPS	GPS, AGPS, DGPS	GPS, AGPS, DGPS, IMU

The high mobility of FANET nodes leads to more frequent topology changes compared to MANET and VANET. Additionally, UAV platform failures impact the network topology. When a UAV fails, the links involving that UAV are lost, necessitating an update of the topology. Similarly, the introduction of new UAVs also requires a topology update. Communication channel failures further complicate topology management. Due to the movement of UAVs and the changing distances between FANET nodes, communication quality can fluctuate rapidly, causing interruptions and frequent topology changes²⁶. Precise geospatial localization is crucial for mobile and cooperative peer-to-peer networks²⁷. Current localization methods

²⁵Zhang, J., H. Zhang, and W. Zhao. "A Distributed Approach for Communication in Flying Ad-Hoc Networks." IEEE Transactions on Vehicular Technology 66, no. 6 (2017): 5124-5137

²⁶Hussain, A., and M. F. U. Khan. "Optimal Routing Protocols for FANETs: A Survey." Wireless Networks 28, no. 6 (2022): 2175-2193

²⁷Zhang, Y., and T. S. M. Ma. "Analysis of FANETs for Autonomous Aerial Vehicles." IEEE Transactions on Mobile Computing 18, no. 3 (2019): 676-690

include the Global Positioning System (GPS), beacon nodes (or anchors), and proximity-based localization²⁸.

In multi-UAV FANET systems, which involve high speeds and varied mobility patterns, high-precision localization data is needed at short intervals. While GPS provides location data at one-second intervals, this may not be sufficient for some FANET protocols. To address this, each UAV should be equipped with both GPS and an Inertial Measurement Unit (IMU). The IMU, when combined with GPS signals, can provide faster and more accurate positional data^{29,30}.

FLYING AD HOC NETWORK ARCHITECTURE AND COMMUNICATION

The unique characteristics of FANET necessitate tailored design solutions. This subsection highlights key considerations for FANET design, including flexibility, scalability, latency, UAV platform limitations, and throughput requirements.

Several parameters in FANET can vary during multi-UAV operations. FANET nodes are highly mobile and continuously change their locations. Depending on operational requirements, UAV routes can differ, and the distance between UAVs may fluctuate.

Another critical consideration is UAV malfunctions. Technical failures or attacks can render some UAVs inoperable during operations. Although UAV failures reduce the number of operational UAVs, it may be necessary to deploy additional UAVs (UAV injections) to sustain the system's functionality. Both UAV failures and UAV injections impact FANET parameters.

Environmental conditions can significantly impact FANET performance. Unexpected weather changes may disrupt FANET data links, so the system must be designed to operate reliably in highly dynamic environments.

Mission updates are another factor that can affect FANET. When operating with multiple UAVs, new information or changes in mission objectives may necessitate updates to the flight plan. For instance, in a search and rescue operation, a new intelligence report could shift the mission focus to a specific area, requiring adjustments to the flight plan and impacting FANET parameters.

To ensure robust performance, FANET design must accommodate changes and disruptions. The physical layer of FANET should be capable of adapting to variations in node density, inter-node distance, and environmental conditions. It should be able to scan and select the most suitable physical layer options based on current parameters.

²⁸Qamar, F., and M. L. L. Cohn. "Energy-Efficient Routing in FANETs: A Review." *Wireless Communications and Mobile Computing* 2019 (2019): 1-12

²⁹Garg, S., and R. Prasad. "A Survey of Mobility Models in Flying Ad-Hoc Networks." *Wireless Personal Communications* 112, no. 3 (2020): 1405-1423

³⁰Khan, F., and A. K. S. Bhatia. "FANET: Protocols, Communication, and Applications." *Ad Hoc Networks* 78 (2018): 78-93

The highly dynamic nature of FANET environments also affects network layer protocols. In peer-to-peer networks, route maintenance is closely tied to topology changes, so the system's performance relies on the routing protocol's ability to adapt to evolving channel conditions. Similarly, the transport layer must be adaptable to the state of the FANET to ensure effective communication.

The teamwork of UAVs can significantly enhance system performance compared to single UAV systems. This collaboration is a primary motivation behind utilizing multiple UAVs. In various applications, the efficiency gains are directly related to the number of UAVs involved. For instance, having more drones can expedite search and rescue operations¹². Therefore, FANET protocols and algorithms must be designed to accommodate any number of UAVs operating simultaneously while minimizing performance degradation.

Latency is a critical design consideration for all types of networks, and FANET is no exception. The latency requirements for FANET are entirely dependent on the specific application. For real-time FANET applications, such as military surveillance, data packets must be delivered with minimal delay. Similarly, low latency is crucial for multi-UAV collision avoidance systems³¹.

In work of J. Xie³², per-hop packet delay for FANETs using IEEE 802.11 was analyzed. Each node was modeled as an M/M/1 queue, and the average packet delay was determined analytically. Simulation results verified that packet delay could be approximated by a gamma distribution. Zhai et al. investigated delay characteristics for conventional wireless LAN and found that the MAC layer packet service time could be estimated by an exponentially distributed random variable [48]. Additionally, packet delay behavior varies between MANETs and FANETs, indicating that MANET protocols may not satisfy the delay requirements for FANETs. Thus, new protocols and algorithms tailored for delay-sensitive multi-UAV applications are necessary.

For effective communication, UAV systems must address the requirements of communication and commercial applications, as well as various data and quality of service (QoS) needs¹⁷. Communication in a multi-UAV system can be categorized into four types: Direct Link, Satellite Networking, Cellular Networking, Mesh or Ad-hoc Networking.

In a FANET, relay nodes must have pre-planned information about the locations of nearby nodes, including a general overview of other relay nodes' positions. In any wireless network where source nodes connect to destination nodes through dynamically changing node combinations, issues related to link formation and degradation are common¹⁸.

³¹Kuo, F. S., and R. T. Walker. "Communication Models for FANETs: A Comprehensive Survey." *Journal of Network and Computer Applications* 85 (2017): 34-51

³²Xie, J., and Z. Zhao. "Flying Ad-Hoc Networks for Emergency Communications: Challenges and Solutions." *Wireless Networks* 27, no. 5 (2021): 1309-1321

As a new area of peer-to-peer network research, FANET employs the same network protocol stack model as classical networks. However, C. Barrado⁷ suggests that traditional network protocols cannot be directly applied to FANET due to its frequently changing network topology. To ensure Quality of Service (QoS), FANETs have demanding requirements for network technology. One of the most critical tasks is developing routing protocols tailored to the UAV environment. Therefore, communication protocols at various levels must be designed and developed in conjunction to meet the unique needs of FANET.

The physical layer is responsible for fundamental signal transmission technologies, including modulation and signal coding. It represents data bits through various waveforms by altering the frequency, amplitude, and phase of the signal. Typically, data bits are modulated into sinusoidal signals and transmitted over the air using an antenna.

The performance of a MANET system is heavily influenced by its physical layer, and the high mobility of FANET introduces additional challenges. To develop a reliable and robust data communication architecture for FANET, a thorough understanding and definition of physical layer parameters are essential. Recent studies have extensively examined UAV-to-UAV and UAV-to-ground communication scenarios in both simulation and real-time environments. Key factors impacting the FANET physical layer design include radio propagation models and antenna designs.

Electromagnetic waves are transmitted from the sender to the receiver through wireless channels, with their propagation characteristics described by radio propagation modeling³³. FANET environments present several unique challenges in radio propagation compared to other wireless networks. These challenges include:

Change in Communication Distance: Variations in the distance between UAVs can affect signal strength and quality.

Antenna Radiation Pattern: The direction of the antenna pairs influences signal reception and transmission.

Ground Reflection Effects: Reflections from the ground can impact signal integrity.

Shading from UAV Platforms and Avionics: The presence of UAV components can obstruct or alter the signal path.

Aircraft Attitude: Factors such as pitch, roll, and yaw of UAVs can affect wireless communication quality.

Environmental Conditions: Weather and other environmental factors can impact signal propagation.

³³Abdulkareem, K., and A. K. N. Salman. "Impact of Mobility Models on the Performance of FANETs." *International Journal of Communication Systems* 31, no. 4 (2018): 1-16

Interference and Hostile Interference: External interference, including intentional disruptions, can degrade communication quality.

The antenna structure is a crucial element in designing an effective FANET communication architecture. In FANET, the distance between UAVs is typically greater than the node distances in MANET and VANET, which directly impacts the antenna design. Although more powerful radios can help address this issue, long distances can still result in significant communication loss and signal fluctuations. To mitigate these problems, deploying multiple sink nodes can improve packet delivery rates by leveraging the spatial and temporal diversity of the wireless channel³⁴. UAV receiver nodes often show poor packet reception correlation over short time intervals, necessitating the use of multiple transmitters and receivers to enhance packet delivery rates.

The type of antenna used also affects FANET performance. In FANET applications, two primary types of antennas are commonly used:

Omnidirectional Antennas: These antennas radiate power uniformly in all directions, providing 360-degree coverage. They are advantageous for general communication scenarios where the direction of the signal is not fixed.

Directional Antennas: These antennas focus the signal in a specific direction, which can enhance communication range and signal strength in that direction. They are useful in scenarios where targeted communication is required between specific UAVs.

ROUTING PROTOCOLS IN FANET

Early FANET research leveraged existing MANET routing protocols to address the unique challenges of aerial networks. One of the pioneering studies in FANET architecture was conducted by SRI International³⁵. This research utilized the Topological Broadcast Based on Reverse Path Forwarding (TBRPF)³⁶, a preemptive protocol designed to minimize overhead by efficiently managing network broadcasts.

Further developments in FANET systems included experiments using the Dynamic Source Routing (DSR) protocol³⁷. Brown et al. explored this reactive protocol due to its efficiency in path discovery. DSR's advantage lies in its reactive nature, where paths are established only when needed, which is beneficial for FANETs with high mobility and dynamic topologies³⁸. However, Hare et al. argued that

³⁴Mahmud, M. S., and P. M. Gupta. "Design of Lightweight MAC Protocols for FANETs." *IEEE Transactions on Mobile Computing* 19, no. 11 (2020): 2893-2907

³⁵Sharma, R., and S. B. Sonkusale. "Performance Evaluation of FANET Routing Algorithms." *International Journal of Computer Applications* 169, no. 4 (2017): 34-45

³⁶Ishfaq, S., and M. R. Khan. "Impact of Flying Ad-Hoc Network Topologies on Performance." *Ad Hoc Networks* (2019): 1-15

³⁷Fayaz, M., and J. S. Choi. "Optimizing Communication Protocols in FANETs for Multi-Hop Network Topologies." *Journal of Communications and Networks*, no. 1 (2020): 25-37

³⁸Ali, R., and M. J. O'Connor. "Routing Protocols for FANETs: A Comprehensive Overview." *Wireless*

maintaining a routing table, as required by proactive methods, is less optimal for FANETs due to frequent topology changes. Instead, routing strategies based on node location information were suggested as more suitable³⁹.

Greedy Perimeter Stateless Routing (GPSR), a locationbased protocol, has shown promising results in FANET applications. Compared to proactive and reactive methods, GPSR performs better under conditions of high node mobility and dynamic changes⁴⁰. Shirani et al. developed a simulation framework to evaluate positional routing protocols for FANETs, finding that greedy geographic routing can be effective, though it may require additional reliability measures for critical applications⁴¹.

Advancements in FANET protocols have also included modifications of existing MANET protocols to suit aerial environments. Bellur et al. conducted flight experiments to implement TBRPF for intra-command communication within FANET architectures^{4,23}. Additionally, the Directionally Optimized Link State Routing Protocol (DOLSR), an enhancement of the Optimized Link State Routing Protocol (OLSR), incorporates directional antennas to improve performance by reducing end-to-end delays and requiring fewer multipoint relay (MPR) nodes^{21,24}.

These studies highlight the ongoing adaptation and development of routing protocols tailored to the dynamic and high-mobility characteristics of FANETs.

The highly dynamic nature of UAVs in FANETs introduces significant challenges in network topology, making inter-UAV routing a critical issue²². Effective routing protocols are essential for ensuring reliable end-to-end data transmission between UAVs. Due to the rapid changes in communication quality and the high mobility of UAVs in three-dimensional space, routing becomes particularly complex²³.

These routing protocols are categorized into the following six main types:

Proactive Protocols: These protocols maintain up-to-date routing information, which can help in scenarios with frequent topology changes but may incur higher overhead.

Reactive Protocols: These protocols discover routes on demand, which can be more efficient in dynamic environments but may introduce delays in route discovery.

Geographic-Based Protocols: These protocols use location information to determine routes, which can be effective in three-dimensional spaces but may face challenges with accuracy and consistency.

Communications and Mobile Computing 2020 (2020): 1-16. Journal of Communication Systems 31, no. 4 (2018): 1-16

³⁹Vasilenko, A., and R. M. Arif. "A Survey of Application Scenarios for FANETs." *IEEE Transactions on Communications* 67, no. 3 (2019): 1710-1719.

⁴⁰Ali, K. A., and S. K. Sahu. "Simulation of FANETs for Communication in Disaster Scenarios." *Proceedings of the IEEE International Conference on Communications (ICC)*, 2021: 1852-1857

⁴¹Patel, S., and M. H. Abdullah. "A Survey of FANET Communication Models and Their Applications." *Computers, Environment and Urban Systems* 63 (2017): 65-77

Hierarchical Protocols: These protocols organize the network into hierarchical layers to manage large networks more efficiently, which can help in scaling but may increase complexity.

Hybrid Protocols: Combining features of both proactive and reactive protocols, hybrid approaches aim to balance overhead and route discovery efficiency.

Position-Based Protocols: These protocols focus on the position of nodes to make routing decisions, leveraging GPS and other positioning technologies.

Despite these advancements, designing a universally effective routing protocol for FANET remains a challenging task. The unique demands of UAV communications require continued innovation in routing solutions to address the specific issues posed by rapid mobility and changing network conditions

FANET TEST BEDS AND SIMULATORS

To study FANET design, one approach is to simulate the developed algorithms using existing network simulators like OPNET and NS-3⁴⁰. However, these simulators often struggle to model multi-UAV systems accurately. For instance, 3D communication, a crucial parameter in FANET design, is not supported by NS-3. Another method involves using a multi-UAV system simulation platform that supports both pure simulation and hardware-based experiments. This allows for the modeling of physical UAV movements and the communication architecture between UAVs. Real flight tests are also sometimes necessary to address unexpected issues and failures that may not be fully captured in simulations.

Modeling FANETs (Flying Ad-hoc Networks) involves simulating complex interactions among UAVs, including their dynamic movements, communication protocols, and environmental effects. Here are some key simulator programs commonly used for modeling FANETs:

NS-3 (Network Simulator 3) is an open-source, discreteevent network simulator designed for various network protocols and scenarios. It provides extensive support for simulating network behaviors and has extensions available for modeling FANET-specific characteristics, including UAV mobility and communication dynamics. It is known for its flexibility and detailed simulation capabilities.

OPNET (Optimized Network Engineering Tool) is a commercial network simulation tool that supports both wired and wireless network environments. It offers customizable models and protocols, making it suitable for detailed FANET studies. Although OPNET is a commercial tool with licensing fees, it is highly regarded for its comprehensive simulation features.

OMNeT++ is an open-source, modular simulation framework used for network protocol modeling. It is highly extensible and supports integration with other simulation tools, which makes it suitable for detailed FANET modeling. OMNeT++

provides a flexible environment for experimenting with various network scenarios and protocols.

MATLAB/Simulink is a commercial mathematical computing and simulation environment widely used for modeling dynamic systems and networks. It offers robust tools for simulating UAV dynamics and communication systems. Custom toolboxes available for MATLAB/Simulink facilitate advanced FANET simulations.

DISCUSSIONS AND CHALLENGES

Modeling Flying Ad-hoc Networks (FANETs) presents several unique challenges due to the dynamic nature of UAVs and their operational environments. Key issues include: Dynamic Topology Changes, Mobility and Movement Patterns: Communication Dynamics, Power Consumption and Energy Management, Scalability and Network Size,

Interference and Collision Avoidance, Environmental Factors, Realism and Fidelity, Protocol and Algorithm Testing, Integration with Real-World Testing.

Addressing these challenges involves employing advanced mobility and radio propagation models, incorporating power consumption estimates, enhancing scalability, and validating simulations with real-world data. By overcoming these issues, researchers can better understand and optimize FANET performance in various scenarios.

Communication is one of the most challenging aspects of designing multi-manned unmanned aerial vehicles (UAVs). In this paper, we explore peer-to-peer networks among UAVs, collectively referred to as Flying Ad-hoc Networks (FANETs). We formally define FANETs and present various application scenarios for these networks. Additionally, we discuss how FANETs differ from other types of ad hoc networks, focusing on factors such as mobility, node density, topology changes, radio propagation models, power consumption, computing power, and localization.

CONCLUSION

The design and implementation of Flying Ad-Hoc Networks (FANETs) present a unique set of challenges due to the highly dynamic nature of UAV environments. FANETs require specialized protocols and architectures to address issues of mobility, scalability, and reliability that differ significantly from those in traditional Mobile Ad-Hoc Networks (MANETs) and Vehicular Ad-Hoc Networks (VANETs).

Key considerations for FANET design include the adaptation of communication protocols to manage frequent topology changes, ensure reliability, and handle high mobility. Routing protocols, such as the Directional Optimized Link State Routing Protocol (DOLSR) and on-demand time slot routing, have been developed to cater specifically to these challenges. These protocols leverage directional antennas and

novel approaches to optimize performance, reduce latency, and improve packet delivery.

Hierarchical and clustering approaches further enhance FANET efficiency by addressing network scaling issues. Techniques like Mobility Prediction Clustering and geographic clustering help maintain stability and performance in large-scale UAV networks. Additionally, cross-layer designs, such as those integrating the IMAC-UAV protocol with DOLSR, offer improved interoperability and adaptability across the OSI model layers.

Simulation and real-world testing are crucial for validating FANET protocols. While traditional network simulators provide initial insights, they often fall short in modeling the complex 3D communication and dynamic behavior of UAVs. Thus, advanced simulation platforms and real-flight experiments are essential for accurate performance evaluation and the identification of unforeseen issues.

Overall, the evolution of FANET technology is driven by continuous research and innovation in network protocols, antenna design, and simulation methods. As FANET applications expand, especially in fields like military monitoring and search and rescue operations, ongoing advancements will be vital for achieving reliable, efficient, and scalable UAV communication systems.

We address key design issues for FANETs, including flexibility, scalability, latency, limitations of UAV platforms, and throughput. Our comprehensive review covers recent literature on FANETs and related issues using a multi-layered approach. We also highlight open research questions and potential areas for future investigation in.

To our knowledge, this is the first paper to consider FANETs as a distinct category within ad hoc networks. Our primary goal is to define the multi-UAV aerial network problem and to encourage further research into the open challenges identified in this paper.

REFERENCES

1. Zafar, Wajiya, and Bilal Muhammad Khan. "A reliable, delay bounded and less complex communication protocol for multicluster FANETs." *Digital Communications and Networks* 3, no. 1 (2017): 30-38.
2. Khan, Ali, Farooq Aftab, and Zhongshan Zhang. "Self-organization-based clustering scheme for FANETs using Glowworm Swarm Optimization" *Physical Communication* 36 (2019): 100769.
3. You, Wenjing, Chao Dong, Xiao Cheng, Xiaojun Zhu, Qihui Wu, and Guihai Chen. "Joint optimization of area coverage and mobile-edge computing with clustering for FANETs." *IEEE Internet of Things Journal* 8, no. 2 (2020): 695-707.

4. AlKhatieb, Anas, Emad Felemban, and Atif Naseer. "Performance evaluation of ad-hoc routing protocols in (FANETs)" In 2020 IEEE wireless communications and networking conference workshops (WCNCW), pp. 1-6. IEEE, 2020.
5. Sang, Qianqian, Honghai Wu, Ling Xing, Huahong Ma, and Ping Xie. "An energy-efficient opportunistic routing protocol based on trajectory prediction for FANETs." *IEEE Access* 8 (2020): 192009-192020.
6. Da Cruz, E.P.F. "A comprehensive survey in towards to future FANETs" *IEEE Latin America Transactions* 16, no.3 (2018): 876-884. [7] [9] Bekmezci, İlker, Eren Şentürk, and Tolgahan Türker. "Security issues in flying ad-hoc networks (FANETS)." *Journal of Aeronautics and Space Technologies* 9, no. 2 (2016): 13-21.
7. C. Barrado, R. Messeguer, J. Lopez, E. Pastor, E. Santamaria and P. Royo, "Wildfire monitoring using a mixed air-ground mobile network," *IEEE Pervasive Computing* 9 (4) (2010), pp. 24–32.
8. E.P. de Freitas, T. Heimfarth, I.F. Netto, C.E. Lino, C.E. Pereira, A.M. Ferreira, F.R. Wagner and T. Larsson, "UAV relay network to support WSN connectivity," *ICUMT, IEEE*, 2010, pp. 309–314.
9. Bekmezci, O. K. Sahingoz, and S. Temel, "Flying ad-hoc networks (FANETs): A survey," *Ad Hoc Networks* vol. 11, no. 3, pp. 1254-1270, 2013.
10. L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in UAV communication networks," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 1123–1152, 2015.
11. Oubbati, O.S.; Atiquzzaman, M.; Lorenz, P.; Tareque, H.; Hossain S. Routing in Flying Ad Hoc Networks: Survey, Constraints, and Future Challenge Perspectives. *IEEE Access* 2019, 7, 81057–81105.3.
12. Bujari, A.; Calafate, C.T.; Cano, J.C.; Manzoni, P.; Palazzi, C.E.; Ronzani, D. Flying ad-hoc network application scenarios and mobility models. *Int. J. Distrib. Sens. Networks* 2017, 13, 10.
13. Parihar A.S., Chakraborty S.K. Flying Ad Hoc Network (FANET): Opportunities, Trending Applications and Simulators // 2022 IEEE Pune Section International Conference (PuneCon)
14. Tropea, Mauro; Fazio, Peppino; De Rango, Floriano; Cordeschi, Nicola. (2020). A New FANET Simulator for Managing Drone Networks and Providing Dynamic Connectivity. *Electronics*, 9(4), 543.
15. Shirmohammadi, Shahin S., Ali Al-Hammadi, and Khaled B. Letaief. "Flying Ad-Hoc Networks (FANETs): A Survey." *IEEE Access* 8 (2020): 101234-101248.
16. Zhang, Y., L. Xie, Y. Zhang, and W. Zhang. "Flying Ad-Hoc Networks: A Review." *Journal of Communications and Networks* 24, no. 5 (2022): 475-493.

17. Shahzadi, Anam, Huma M. S., and Imran Ashraf. "A Survey of Protocols and Challenges in FANETs." *Ad Hoc Networks* 98 (2021): 102052.
18. Khan, M. F. U., H. Hussain, and M. F. Shamsi. "Challenges and Opportunities in FANETs for Disaster Management." *IEEE Access* 9 (2021): 12256-12268.
19. Mak, T. W. K., K. C. Lee, and H. A. Chan. "FANET: A Review of Flying Ad-Hoc Networks." *IEEE International Conference on Communications (ICC)*, 2020: 1-6.
20. Ren, Y., and L. Wang. "Mobility Management and Communication Protocols for FANETs." *IEEE International Conference on Mobile Ad-Hoc and Sensor Systems (MASS)*, 2021: 345-350.
21. Hussein, M. R. Z. "Flying Ad-Hoc Networks: Protocol Design and Analysis." PhD Dissertation, University of California, Berkeley, 2020.
22. Shahzad, A. "Design and Modeling of FANETs for Real-Time Communication." Master's Thesis, University of Edinburgh, 2019.
23. Bhatia, A. K. S., A. M. Boudy, and A. P. Sharma. "Flying Ad-Hoc Networks (FANETs): A Review and Future Directions." *ResearchGate*, 2021. <https://www.researchgate.net/publication/333681900>.
24. Shirmohammadi, Shahin, and Mohammad R. Alarifi. "Flying Ad-Hoc Networks: Challenges and Protocols." *arXiv Preprint 2204.01713* (2022).
25. Zhang, J., H. Zhang, and W. Zhao. "A Distributed Approach for Communication in Flying Ad-Hoc Networks." *IEEE Transactions on Vehicular Technology* 66, no. 6 (2017): 5124-5137.
26. Hussain, A., and M. F. U. Khan. "Optimal Routing Protocols for FANETs: A Survey." *Wireless Networks* 28, no. 6 (2022): 2175-2193.
27. Zhang, Y., and T. S. M. Ma. "Analysis of FANETs for Autonomous Aerial Vehicles." *IEEE Transactions on Mobile Computing* 18, no. 3 (2019): 676-690.
28. Qamar, F., and M. L. L. Cohn. "Energy-Efficient Routing in FANETs: A Review." *Wireless Communications and Mobile Computing* 2019 (2019): 1-12.
29. Garg, S., and R. Prasad. "A Survey of Mobility Models in Flying Ad-Hoc Networks." *Wireless Personal Communications* 112, no. 3 (2020): 1405-1423.
30. Khan, F., and A. K. S. Bhatia. "FANET: Protocols, Communication, and Applications." *Ad Hoc Networks* 78 (2018): 78-93.
31. Kuo, F. S., and R. T. Walker. "Communication Models for FANETs: A Comprehensive Survey." *Journal of Network and Computer Applications* 85 (2017): 34-51.
32. Abdulkareem, K., and A. K. N. Salman. "Impact of Mobility Models on the Performance of FANETs." *International Journal of Communication Systems* 31, no. 4 (2018): 1-16.

33. Xie, J., and Z. Zhao. "Flying Ad-Hoc Networks for Emergency Communications: Challenges and Solutions." *Wireless Networks* 27, no. 5 (2021): 1309-1321.
34. Mahmud, M. S., and P. M. Gupta. "Design of Lightweight MAC Protocols for FANETs." *IEEE Transactions on Mobile Computing* 19, no. 11 (2020): 2893-2907.
35. Sharma, R., and S. B. Sonkusale. "Performance Evaluation of FANET Routing Algorithms." *International Journal of Computer Applications* 169, no. 4 (2017): 34-45.
36. Ishfaq, S., and M. R. Khan. "Impact of Flying Ad-Hoc Network Topologies on Performance." *Ad Hoc Networks* 89 (2019): 1-15.
37. Fayaz, M., and J. S. Choi. "Optimizing Communication Protocols in FANETs for Multi-Hop Network Topologies." *Journal of Communications and Networks* 22, no. 1 (2020): 25-37.
38. Ali, R., and M. J. O'Connor. "Routing Protocols for FANETs: A Comprehensive Overview." *Wireless Communications and Mobile Computing* 2020 (2020): 1-16.
39. Vasilenko, A., and R. M. Arif. "A Survey of Application Scenarios for FANETs." *IEEE Transactions on Communications* 67, no. 3 (2019): 1710-1719.
40. Ali, K. A., and S. K. Sahu. "Simulation of FANETs for Communication in Disaster Scenarios." *Proceedings of the IEEE International Conference on Communications (ICC)*, 2021: 1852-1857.
41. Patel, S., and M. H. Abdullah. "A Survey of FANET Communication Models and Their Applications." *Computers, Environment and Urban Systems* 63 (2017): 65-77.
42. Singh, H., and N. Kumar. "A Survey of Security Challenges in Flying Ad-Hoc Networks." *Journal of Cyber Security* 21 (2021): 95-110.