A Survey of Security in UAVs and FANETs: Issues, Threats, Analysis of Attacks, and Solutions

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Abstract—Thanks to the rapidly developing technology, unmanned aerial vehicles (UAVs) are able to complete a number of tasks in cooperation with each other without need for human intervention. In recent years, UAVs, which are widely utilized in military missions, have begun to be deployed in civilian applications and mostly for commercial purposes. With their growing numbers and range of applications, UAVs are becoming more and more popular; on the other hand, they are also the target of various threats which can exploit various vulnerabilities of UAV systems in order to cause destructive effects. It is therefore critical that security is ensured for UAVs and the networks that provide communication between UAVs.

This survey seeks to provide a comprehensive perspective on security within the domain of UAVs and FANETs. Our approach incorporates attack surface analysis and aligns it with the identification of potential threats. Additionally, we discuss countermeasures proposed in the existing literature in two categories: preventive and detection strategies.

Our primary focus centers on the security challenges inherent to FANETs, acknowledging their susceptibility to insider threats due to their unique characteristics. Consequently, our study involves the simulation and analysis of four distinct routing attacks on FANETs. Hence, this study transcends a standard review by integrating an attack analysis based on extensive simulations.

Finally, we rigorously examine open issues, and propose research directions to guide future endeavors in this field.

Index Terms—Unmanned aerial vehicle (UAV), Flying ad-hoc network (FANET), Security, Cryptography, Intrusion Detection, Attack Analysis

I. INTRODUCTION

U NMANNED aerial vehicles (UAVs) are aircraft capable of being flown without a human pilot or any other crew on board [1]. Commercial UAVs are aircrafts that are intended to be used for business purposes. With a CAGR of 28.58% during the projection period, it is expected that the global market for commercial UAVs will expand rapidly, increasing from \$8.15 billion in 2022 to \$47.38 billion by 2029 [2]. Gartner projects that there will be over one million UAVs operating by 2026, representing a staggering increase compared to the 20,000 UAVs currently in use for retail deliveries [3].

In particular, the ability to work autonomously and collaboratively without need for human intervention is pioneering the expansion of UAV applications. UAVs are now used within

Sevil Sen is with Computer Engineering Department, Hacettepe University, Ankara, Turkey (e-mail: ssen@hacettepe.edu.tr) military missions [4], on search and rescue operations [5], [6], on target tracking assignments [7], as well as in environment protection studies [8], agricultural missions [9], and many other areas where their benefits fit the need. Numerous defense ministries worldwide are investing in UAVs capabilities as a means to reducing troop casualties, and as a cost-effective alternative to the use of manned aircraft. However, with the increasing use and growing interest of UAVs in both civil and military applications, UAVs have become a clear target for cyber attacks [10], [11].

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UAVs can communicate with each other (UAV-to-UAV) and/or with a base station (UAV-to-ground station) via wireless links. Hence, the use of wireless connections in UAVs makes the network inherently vulnerable to eavesdropping and active interference attacks. While some attackers target communication links between UAVs, others target UAV-based features such as software, sensors, or hardware.

The high mobility of UAVs makes the network topology dynamics different from Mobile Ad hoc Networks (MANETs) and Vehicular Ad hoc Networks (VANETs). For that reason, a new type of ad hoc networks called Flying Ad hoc Networks (FANETs) has emerged and has become a popular area of research areas in recent years [12]. In addition to single UAV operations, the collaborative use of UAVs as FANETs now feature in many applications such as performing search and rescue operations within a limited or confined area [13], as well as international border surveillance [14], logistics [15], forest fire monitoring and control [16], and agricultural remote sensing systems [17].

Although FANETs is a subset of MANETs, it differs from other types of ad hoc networks by its very characteristics. One of the most obvious differences is its dynamic topology, which changes due to the high speed nature of UAVs. UAVs move in 3D, unlike the nodes in MANETs and VANETs. Their mobility patterns also differ compared to other ad hoc network types. For example, they may fly together as a group in one direction and periodically move towards the controller ground system to complete certain missions. In addition, due to the large flight area potential, the node density of FANETs is lower than other ad hoc networks. Another difference relates to platform restrictions, since UAVs allow for minimally-sized batteries, hence the problem of rapid energy depletion comes to the fore.

With the accelerated use of UAVs in numerous tasks and applications, attackers have focused their interest on not only the devices but also the dynamic networks that support and operate high-speed UAVs. UAVs and their networks are exposed to

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attacks due to various vulnerabilities such as having nodes with limited battery power, the use of wireless links, and protocols based on the cooperativeness of nodes within in the networks. Considering the popularity of UAVs and the future of FANETs, it is important to outline the vulnerability landscape and effective attacks, and to discuss possible solutions that may be employed against them.

The primary objective of this study is to analyze the system's attack surface, identifying potential points of vulnerability. Expanding on this analysis, the study refines understanding by categorizing related attacks into a taxonomy based on the identified entry points within the attack surface. Additionally, the study discusses the proposed solutions for the prevention and detection of attacks against UAV devices and networks.

Moreover, this study examines attacks against UAV communication within the routing layer through realistic network simulations. While previous studies often focused on specific aspects of UAV security, this research offers a comprehensive survey encompassing security issues and proposals for both FANETs and UAVs. Notably, this survey paper does not solely rely on theoretical analyses but also conducts practical simulations to assess real-world implications.

The key contributions of this survey paper can be summarized as follows:

- The unique characteristics of UAVs and networks of UAVs are presented in details, and then analyzed from a security perspective.
- Attack surface analysis of UAVs and FANETs is introduced and taxonomy of attacks is presented with detailed categories based on the identified entry points within the attack surface.
- Inspired by a lack of analysis of attacks using realistic network scenarios in the literature, the current study implements and deeply analyzes four attacks against the routing of FANETs.
- Security solutions proposed for preventing and detecting such attacks are reviewed and their limitations discussed.
- Open issues and future research directions within the research domain are discussed in detail.

The organization of the survey is shown in Figure 1. Section-II discusses existing surveys for the security of FANETs and UAVs with their limitations, and emphasizes the unique contributions offered by the current study. Section-III provides a background of UAVs and FANETs and discusses their characteristics from a security point of view. Section-IV defines the possible enrty points of UAVs and FANETs. Section-V categorizes security attacks against UAVs in the light of attack surface analysis. Section-VI presents simulations and analysis of attacks against networks of UAVs using realistic simulation parameters. Section-VII then summarizes the existing security solutions in the literature, grouping them under two subsections as prevention and detection. Lastly, Section-VIII outlines the limitations of the proposed studies and discusses open research areas, which is followed by a conclusion in Section-IX. The list of acronyms used in this manuscript can be found in Table I.



Fig. 1. Survey Organization

II. RELATED WORK

The first study that reviewed security issues in FANETs was [18], which not only summarized the proposed studies for secure communication in FANETs, but also gave some exemplar security solutions proposed for MANETs. However, since it was one of the first survey studies, it consisted of only a limited number of initial security solutions that had been proposed in the literature, and most of these studies were proposed for MANETs. Analysis of the existing security mechanisms proposed for MANETs and VANETs was presented as one of the open research areas [18].

Similarly, [19] focused on the security requirements of routing protocols for UAVs, and was also the first study to address this area in terms of vulnerabilities and network attacks. Attacks are examined according to three phases of routing protocols: routing discovery, route maintenance, and data forwarding. For security countermeasures, cryptographyand trust-based systems, and intrusion detection systems were discussed. Similarly, the vulnerabilities of UAV communication systems, the risks associated with data transmission and processing, and the need for secure communication protocols were discussed in [20]. Another survey [21] reviewed the security issues of FANETs, in addition to FANET communication and mobility models. However it did not give a specific classification of threats to FANETs or UAVs. A limited number of security solutions were discussed in the study, and it was emphasized that traditional security approaches are not directly applicable to FANETs due to their latency and heavy computation [21].

TABLE I LIST OF ACRONYMS

2D	Two dimensionals	MEC	Mobile Edge Computing
2D 3D	Three dimensionals	MEMS	Micro Electro Mechanical Systems
50 50	Fifth generation	MITM	Man in the Middle
ANN	Artificial Neural Network	MI	Machine Learning
AODV	Ad-hoc On Demand Distance Vector	NR	Naive Bayes
ARP	Address Resolution Protocol	NN	Neural Networks
	Area Under the Curve	DCB	Printed Circuit Board
CNN	Convolutional Neural Networks		Packet Delivery Patio
DDoS	Distributed daniel of Service	DIS	Physical Lover Security
DNN	Deep Neural Network	DEDD	Poute Error Dackets
DoB	Deep Neural Network	DE	Route Error Lackets
Dob	Daniel of Service		Random Forest Recurrent Neural Network
DDJ	Deep Painforcement Learning	DDED	Poute Perly Packet
DSP	Dynamic Super Pesolution	RREI	Route Reply Lacket
DSSS	Direct Sequence Spread Spectrum	RSS	Received Signal Strength Difference
DSSS	Decision Tree	RSS	Received Signal Strength Indicator
E2E	End-to-end	RSUs	Road Side Unites
FANET	Elving Ad hoc Network	RTI	Return-to-Launch
FUSS	Frequency Hopping Spread Spectrum	PTT	Return-to-Lauren
FI	Ederated Learning		Round The Thic Random Waynoint Model
FPR	False Positive Rate	SAODV	Secure Ad-hoc On Demand Distance Vector
GBS	Ground Base Station	SDN	Software Defined Networking
GMM	Gauss Markov Mobility	SDR	Software defined Padio
GPS	Global Positioning Stations	SDR	Signal Strength Intensity
	Human Immune System	SVM	Support Vector Machines
	Intrusion Detection System	SVN	Support vector Machines
IMU	Inertial Measurement Unit	TCP	Transmission Control Protocol
IoD	Internet_of_drone	Tdoa	Time Difference of Arrival
IoD	Internet of Things		Instant Key Disclosure
IBIG	Joint Bi level Image Experts Group	UAVe	Unmanned Aerial Vehicles
KNN	K Nearest Neighbors		User Datagram Protocol
	Linear Degression	VANET	Vehicular Ad hoc Networks
LIC	Long Term Evolution	WiEi	Wireless Eidelity
MAC	Media Access Control	Wi-MAY	Worldwide Interoperability for Microwaya Access
MANET	Mobile Ad hoc Networks	VOP	eXclusive OP
MANEIS	MODILE AU HOC INCLWORKS	AUK	CACIUSIVE OK

In [22]–[25], the authors presented potential threats against UAV systems, but FANET security was not covered. In [22], the UAV based-system attacks were briefly described with an overview, and then the authors focused on charging systems and battery attacks, and appropriate countermeasures. However, since UAV battery consumption attacks are new attacks, it was noted that the literature contained no fixed security solutions. Along with this issue, effective detection systems and artificial intelligence security systems were also highlighted as open research issues in [22].

Zhi et. al. [23] discussed UAV system threats by dividing them into three groups: sensor, communications, and multi-UAVs. Wi-Fi security was significantly emphasized as most UAVs require Wi-Fi connectivity for the purpose of remote control. In addition, the study revealed that sensor attacks affect the behavior of UAVs at a high level, as UAVs receive assistance from sensors such as gyroscopes to ensure balance and compass sensors to determine direction. However, compared to other surveys, the study contained only a limited number of attacks.

In [24], attacks that hinder the secure position estimation of drones are analyzed and categorized into two main classes: localization error attacks and other attacks. In addition, the authors discussed security analysis techniques, including security verification tools and methods. In [25], without giving a specific classification, some attacks against UAVs are covered such as DoS, man-in-the-middle, and de-authentication, and how these attacks exploit the vulnerabilities of different UAV applications is presented. The authors discuss applications of machine learning, blockchain, and SDN-based approaches to provide the security of UAVs only, not FANETs.

In [26]–[28], the security requirements, vulnerabilities, and privacy issues of UAVs were discussed, and included both physical threats as well as cyber threats. In [26], the authors conducted a brief review of the architecture and communication setup of UAVs, which have different domains of usage such as military and civilian, while they also summarized existing countermeasures for security issues. They included detailed explanation of not only the security countermeasures for civil, government, and military UAVs, but also the network, communication, data, and forensic security solutions for all types of UAVs. However, since they focused on countermeasures, the area of potential attacks was reviewed only briefly.

Only civil drone security and privacy issues were covered in [27], and emphasized vulnerabilities aimed at assuming flight control and landing. For this reason, the authors divided cyberattacks into two groups: attacks on flight control and base stations, and attacks on data links. Future research topics of UAV communication were emphasized, and especially FANET security and detection systems. In another recent survey [28], attacks targeting UAV networks were categorized into physical and logical. This survey provided a broad overview by categorizing all non-physical attacks within the logical category. However, refining the classification of these attacks represents a critical step toward implementing more effective security solutions for UAV networks.

A recent survey [29] classified threats into eight groups according to attack vectors (physical, malware, sensor, communication, network, supply chain, hardening defects, miscellaneous) and presented an associated gap analysis. In another recent survey [30], security issues are divided into four groups: sensor-level, hardware-level, communicationlevel, and software-level, and then comprehensively analyzed the countermeasures taken against each type of attack in the literature. In addition, privacy threats were also examined in three classes: individual risks, organization risks, and UAV risks. Unlike other surveys, the study also examined the basic features of UAVs under the headings of hardware, software, sensors, and communication. In this respect, this survey formed a good foundation for new researchers. However, their review of FANETs from a security perspective and potential solutions for them was very brief.

Similarly, in [31], security issues have been categorized into three groups based on the critical components of UAVs: hardware, software, and communication. However, unlike [30], fewer attacks have been discussed for each category, and these attacks have not been individually explained in detail. Emerging defense technologies have been discussed; nonetheless, this study does not handle sensor attacks nor does it outline measures against such attacks. Consequently, this study offers a general overview rather than a comprehensive examination.

In [32], threats targeting UAVs have been categorized into four groups: network, software, payload, and intelligent security. Differing from other surveys, it addresses attacks aimed at intelligent-based security solutions for UAVs. The study examines attacks to exploit machine-learning-based algorithms by manipulating data or generating malicious adversarial samples. However, it does not discuss countermeasures for these specific attacks, and limited attacks have been presented for other categories as well.

There have also been a few studies [33], [34] that have highlighted the security and challenges of ad hoc networks, namely MANET, VANET, and FANET, in the literature. Since the scope of these studies was clearly broad, attack classifications and countermeasures were not sufficiently comprehensive. One of the comprehensive reviews in the literature was given in [35]. The study not only evaluated possible threats to UAVs according to different connection and node types, but also focused on FANET routing, characteristics, communication privacy, and security. This study presented security solutions by classifying threats and security solutions for FANETs according to the four groups of the OSI layer. However, as noted by the authors, some recent studies related to software-defined networking (SDN), machine learning, and 5G technologies were not included. Moreover, hardware-based attacks are not discussed in the study.

A summary of all current studies is presented and compared in Table II and Table III respectively. Almost all previously published surveys have maintained a focus on the general security of UAVs, but the research into the security of FANETs has been inadequate. Typically, these studies do not delve into the security implications arising from the characteristics specific to FANETs. Moreover, while all previous surveys in the literature have reviewed potential threats and solutions on a theoretical basis, there has been no research published in the current literature that has comprehensively analyzed the impact of these attacks on UAVs. The analysis of the four attacks presented in our previous study [36] has been extended in the current study with more realistic scenarios.

One important contribution that our study stand out for is the attack surface analysis. Attack surface analysis enables a more comprehensive understanding of the security landscape, not only by introducing new collaborations with emerging technologies but also by thoroughly exploring all possible entry points. As UAVs and FANETs evolve and interact with various technologies, understanding and addressing these diverse entry points are valuable for developing secure-bydesign strategies.

Our study presents an attack taxonomy based on the analysis of attack surfaces. While various surveys offer diverse attack taxonomies, some of them [18] [27] [19] [23] [24] [20] [28] are not comprehensive enough as shown in Table II. Moreover, our study stands out for its comprehensive attack coverage. While many review studies present and discuss security countermeasures in UAVs and FANETs, our study provides a detailed analysis of these studies and discusses potential research directions rigorously, hence pave new ways for researchers. To the best of our knowledge, this work extensively explores research directions such as architectural aspects, multi-level security, and the role of the Ground Base Station (GBS) asset in security, contributing detailed discussions not previously elaborated upon. With the acceleration of research efforts in UAV security since 2020, we believe that such an inclusive new review study, which encompasses both a review based on the attack surface analysis and an attack analysis with simulations, will be beneficial for researchers.

III. BACKGROUND

Advancements in technology have led to the widespread popularity of UAVs, enabling their versatile applications across various real-world scenarios. While specific applications might favor the use of a single UAV, there are limitations to what operations a sole UAV can effectively execute. Single UAVs encounter challenges in completing missions when faced with rapid battery depletion, extended mission duration, potential electronic system failures due to external or internal factors, or susceptibility to targeting by attackers. These factors significantly hinder the effectiveness of single UAV operations. In these scenarios, FANETs are recommended, as they allow multiple UAVs to join a common network and execute complex tasks in an organized manner [37]. Although FANETs inherits certain features from MANETs and its sub-classes, it also presents differences due to the very characteristics of UAVs such as their high mobility, unpredictable movements, and frequently changing network topology. Subsequently, such characteristics of UAVs are detailed along with the relevant security perspective.

TABLE II Outline of recent surveys on UAV' security

Reference	Year	Taxonomy of Attacks	Description of Content
[18]	2016	by ad hoc networks;	Ad hoc network security issues,
		- Eavesdropping	brief discussion on FANET
		- Modification and Fabrication	communication security.
		- Selfishness	
[27]	2016	by attacks;	Civilian drone security and
		- Flight control and base station	privacy requirements.
		- Data link	
[19]	2017	by routing protocol attacks;	Focused on routing protocol,
		-Passive	network security and
		-Active	countermeasures.
[21]	2019	No specific classification	Security issues in FANETs.
[23]	2020	by attacks;	UAVs security and privacy
		- Sensor	are reviewed briefly.
		- Communication links	, and the second s
		- Multi-UAVs	
[26]	2020	No specific classification	Use of UAVs, their applications,
		1	potential attacks, and countermeasures are highlighted.
[25]	2021	No specific classification	UAV communication security,
		1 A	potential attacks and solutions.
[24]	2021	by attacks that hinder the drones' positions:	Security, privacy, availability
		- Localization error attacks	authenticity, confidentiality,
		- Others	and and countermeasures.
[22]	2022	by attacks:	Describes UAV-based-system
[22]	2022	- UAVs-based systems	attacks: focusing on hattery
		- UAVs-charging system attacks	and charging system security
[29]	2022	by classification:	Describes attacks and
[27]	2022	- Confidentiality-Integrity-Availability-Privacy	countermeasures with gap analysis
		- Threat vectors	counterinteasures with gap analysis.
[35]	2022	by threat vectors and by OSL Laver:	LIAV and FANET security
[55]	2022	- Physical	EANET characteristics
		Data link	and countermassures
		- Data IIIK Network	and countermeasures.
		- INCLWOIK	
[20]	2022	by wireless communication threats:	Focused on DHV and
[20]	2022	Navigational threats	cellular communication security
		Data injecting and altering attacks	central communication security.
		- Data injecting and altering attacks	
		Software threats	
[30]	2023	- Software uncats	Security privacy and
[50]	2025	- Hardware	countermeasures are explained
		- Haldward	countermeasures are explained.
		- Soltware	
		Communication	
[28]	2022	- Communication	Potential attacks and provention methods are discussed
[20]	2025	Dy classification, Physical and Logical	Potential attacks and prevention methods are discussed.
[21]	2022	- Flysical and Logical	Security and amorging defense tech are presented
[31]	2023	Uardwara	Security and emerging defence teen. are presented.
		- Haluwale	
		- Software	
[20]	2022	- Communication	Attacks and defence systems are symbolic ad
[32]	2023	Notwork	Auacks and defense systems are explained.
		- INCLWOIK	
		- SUILWALE Devload	
		- rayloau Intelligent	
Our Starlar	2024	- memgent	Attacks and constants constants
Our Study	2024	by anack surface analysis;	Attacks and countermeasures,
		Communication Lavera	anaux allalysis,
		- Communication Architecture	
		- Communication Architecture	

 TABLE III

 COMPARISON OF OUR SURVEY WITH EXISTING SURVEYS BASED ON DIFFERENT CRITERIA

Study	Year	Security Impacts	Attack Surface	Taxonomy of Attacks	Attack Coverage	Focus on FANEts	Attack Analysis	Countermeasures	Open Issues
[18]	2016	×	×	×	×	 ✓ 	×	×	~
[27]	2016	×	×	 ✓ 	д	×	×	limited	~
[19]	2017	д	×	 ✓ 	×	 ✓ 	X	 ✓ 	×
[21]	2019	×	×	×	×	 ✓ 	×	×	~
[23]	2020	×	×	 ✓ 	×	X	X	X	×
[26]	2020	×	×	×	×	×	×	 ✓ 	~
[25]	2021	×	×	×	×	×	×	 ✓ 	~
[24]	2021	×	×	 ✓ 	д	X	X	 ✓ 	~
[22]	2022	×	×	 ✓ 	д	×	×	limited	~
[29]	2022	×	×	 ✓ 	×	×	×	 ✓ 	~
[35]	2022	д	×	 ✓ 	д	 ✓ 	×	 ✓ 	~
[20]	2022	×	×	 ✓ 	×	×	×	 ✓ 	~
[30]	2023	×	×	 ✓ 	 ✓ 	×	×	 ✓ 	~
[28]	2023	×	×	 ✓ 	×	×	×	 ✓ 	~
[31]	2023	×	×	 ✓ 	×	×	×	v	~
[32]	2023	×	×	 ✓ 	×	×	×	 ✓ 	~
Our survey	2023	 ✓ 	 Image: A start of the start of	 ✓ 	~				

 \checkmark : mentioned, \varkappa : not mentioned, ∂ :partial information

1) Node Mobility & Dynamic Topology: FANETs differ from other ad hoc networks due to UAVs' exceptional node mobility. These networks possess highly dynamic topology due to frequent changes in node positions. Mobility models differ in FANETs according to its application. UAVs might follow predetermined paths or move randomly [38]. They might exhibit independent movement or move collectively in group-based models. Unlike nodes in MANETs and VANETs, they maneuver in 3D space.

Security Impacts: The highly dynamic nature of the network topology poses a significant challenge in differentiating between normal and abnormal behaviour. For instance, identifying a node that is sending routing misinformation becomes intricate, as it could be an attacker or simply outdated. Furthermore, creating secure systems within dynamically changing environments poses significant architectural challenges.

Moreover, high-level mobility can impact security in both positive and negative ways. The mobility of targets, on one hand, can serve to mitigate the impact of attacks directed towards them. Conversely, the mobility also enables attackers to easily evade security measures.

2) Node Density: Node density refers to the average number of UAVs per unit area [38], exhibits a spectrum ranging from low to high, influenced by various factors including usage areas, sky distribution, applications, and UAV types deployed. If UAVs possess high speeds and wide transmission ranges, their density tends to diminish as the distances separating them could extend across several kilometers [39]. Consequently, node density in FANETs is typically observed to be lower compared to both MANETs and VANETs.

Security Impacts: In scenarios with high node density, certain attacks like sinkholes can be particularly effective due to the increased connectivity. Such attacks exploit the density by attracting and redirecting network traffic, posing significant security risks. However, high node density can also positively influence distributed and collaborative security solutions [40]. Nodes in these dense networks are better equipped to detect intrusions locally and collaborate with neighbors to address insufficient local detection, enhancing overall security.

Conversely, in low-density scenarios where UAVs or nodes are sparsely distributed across vast areas, security concerns shift towards ensuring coverage, connectivity, and vulnerabilities due to larger communication ranges and reduced monitoring. In such environments, attacker nodes can evade detection more easily, especially within voting-based systems.

3) Energy Consumption: In FANETs, energy consumption is still a critical design concern, particularly considering the utilization of mini UAVs powered by low-capacity batteries [41]. This limited power source underscores the pressing need for innovative lightweight solutions, representing a substantial focal point for ongoing research within this domain [42].

Security Impacts: UAVs are vulnerable to attacks due to their low energy capacity. In particular, sleep deprivation attacks [43] may be attempted right up until all available energy has been used. Battery attacks have several objectives, including battery drainage, leakage, unauthorized configuration, overcharging to overheat the battery, and draining energy [22].

Moreover, implementing security solutions for FANETs, which require extensive computation, poses a challenge. Lightweight algorithms and energy-efficient solutions are necessary for ensuring a secure network. This demands a careful balance between lightweight solutions and robust security measures to maintain network functionality while safeguarding against potential threats.

4) Radio Propagation Models: Such molels simulate how radio signals propagate through the airspace, directly impact the communication range and quality of wireless links between UAVs [44]. FANETs, unlike MANETs and VANETs, operate at higher altitudes, affording better line-of-sight between sender and receiver. This altitude advantage minimizes signal corruption and environmental interference, enhancing radio signal effectiveness.

Security Impacts: Accurate radio propagation models are pivotal for maintaining secure communication and mitigating vulnerabilities. Erroneous models can result in connectivity misjudgments, leading to weak or non-existent communication coverage areas, effectively creating blind spots. These inaccuracies may offer opportunities for attackers to exploit vulnerabilities covertly, launching disruptive attacks or infiltrating the network undetected. On the other hand, FANETs' improved radio propagation aids security solutions, allowing easier monitoring of attackers by neighboring nodes without signal disruptions between UAVs or GBS.

5) Localization: Localization means determining the location of each UAV [44]. Localization techniques, such as GPSbased positioning, Inertial Measurement Unit (IMU)-based positioning, sensor fusion, and computer vision methods, play a pivotal role in many applications.

Security Impacts: UAV systems require accurate location information in short time intervals due to their high speed of application and dynamic topology. These techniques are vital for establishing trusted communication channels, enforcing access control policies, and validating the identity of UAVs within a networked environment. Inaccurate or compromised localization data can result in misidentified or spoofed locations of UAVs, leading to various security threats. Moreover, with the advent of GPS spoofing and jamming attacks, the risk amplifies further as these can maliciously alter the latitudinal and longitudinal information of UAVs or disrupt sensor data transmissions.

6) Communication Architecture: FANET communication architecture is defined by a set of rules and processes governing how UAVs communicate among themselves or with GBS, exchange information, and establish connections. This significant role in defining communication architecture also determines the network's resilience against security threats. Communication architectures vary according to the application areas of UAVs. However, there is no definitive research that has proven which architecture works best [37]. Communication architecture is classified into two main groups [35]; centralized and decentralized.

In *Centralized Communication* architecture, each UAV communicates directly with a central controller. Since the UAVs cannot communicate with each other in this architecture, all data traffic is directed by the central controller [45].

The use of *Decentralized Communication* involves UAV-UAV interaction that occurs in decentralized networks, either directly or by hopping over other nodes. Without need for a centralized controller, this communication form is provided dynamically by FANETs [35]. In such systems, UAVs communicate within the group, and the base station is generally not included in these communications. Only selected UAVs are connected to the GBS, ensuring communication only between certain UAV groups [46].

Security Impacts: Network centralization raises security issues and implies a need for trust between all nodes in the system. Blockchain, with its features such as decentralization, immutability, security, and transparency, serve as distributed ledger platform that can facilitate secure and transparent transactions without the need for a central authority, therefore it has the potential to address this issue. The capacity of blockchain to offer a secure and tamper-proof record of transactions is one of its main advantages [47]–[49]. This can be especially helpful in FANETs, where UAVs may need to securely and reliably share data and make decisions based on it. However,

the use and deployment of blockchain in UAVs with energy, computation, data storage resource constraints needs further examination.

Centralized communication poses a potential single point of failure, presenting a significant security vulnerability that can impact the entire network in the event of an attack. Despite this vulnerability, central points boast higher processing capacities, enabling the implementation of complex security solutions and algorithms. Additionally, their broader network perspective allows these centralized solutions to potentially detect collaborative and distributed attacks across the network. However, decentralized security solutions enable the detection of specific attacks at a local level within each UAV, potentially accelerating attack detection and response times. Hybrid architectures, combining aspects of both centralized and decentralized approaches, try to strike a balance between control and autonomy. However, such hybrid models may inherit vulnerabilities from both centralized and decentralized systems. While the blockchain technology is a promising alternative for providing decentralization, depending on how it is used, it can also have certain limitations, such as significant latency, throughput, and block size [50], [51].

To sum up, as outlined in Table IV, MANETs, VANETs, and FANETs have different characteristics, hence are faced with different security challenges.

A. Routing Protocol

As UAVs perform their tasks, the nodes must communicate both with each other and also with the GBS. While establishing this communication, routing protocols are designed to provide real-time data transmission, to reduce processor and energy costs, and to adapt the dynamic changing topology. Due to the characteristics of FANETs, new routing protocols should be presented for such highly dynamic networks, or routing protocols developed for MANETs should be adapted to the highly dynamic structure of FANETs. Hence, in the literature, certain routing protocols proposed for MANETs have been extended and redesigned to handle issues such as broken link recovery [52], and security [53]. Routing protocols for FANETs can be examined under five classes [54] as shown in Figure 2. For a comprehensive overview of recent advancements in FANETs routing, interested readers may refer to the recent survey [55].

IV. ATTACK SURFACE OF FANET

The term "attack surface" refers to all the potential entry points on a system, system component, or environment where an attacker could attempt to breach it, have an impact there [56]. Attack surfaces constantly fluctuate as a system incorporates new components or interacts with existing ones. The categories of vulnerability, however, often stay the same. An attack surface diagram offers a comprehensive perspective on all possible flaws within a system. Therefore, in this study, we firstly classify the potential entry points and the landscape of threats against UAVs and FANETs in Figure 3, and then correlate them with the potential attacks targeting

	MANETS	VANETS	FANFTs
		VAREIS	TARLIS
Devices	laptops, cell phones, etc.	vehicles, RSUs	UAVs, GBSs
Node density	medium/high	medium/high (city centers)	low
Mobility and speed	- 2D mobility	- 2D mobility	-3D mobility
	- low speed (7-20 km/h)	- medium speed (20-130 km/h)	- high speed (above 720 km/h)
Topology changes	medium	high	high
Energy constraints	high	low	high for small UAVs
Security requirements	low or high	high	high
	(application dependent)		
Radio propagation	low	low	high
Localization	GPS	GPS	GPS and IMU

 TABLE IV

 COMPARISON OF FANETS WITH MANETS AND VANETS

Routing Protocols



Fig. 2. Classification of routing protocols in FANETs

these categories depicted in Figure 4. Each entry point is discussed below.

A. Insider Threats

Insiders are legitimate system users with a high attack potential. They often posses authenticated access to sensitive information [57]. They may also be aware of the weaknesses in the implemented operation systems and processes. Unlike external attackers, whose attack traces are difficult to conceal, malicious insiders' activities are often harder to detect. Consequently, threat actors have a strong incentive to use the insider threat vector, and this motivation is expected to increase. These threats can come in various forms, ranging from unintentional actions, such as accidental information disclosure or data alteration, to deliberate misuse or neglect of safety measures [58].

Within the dynamic and decentralized nature of FANETs, insider threats pose additional challenges, especially given the crucial reliance on trust. Distinguishing between malicious intent and legitimate actions becomes more challenging in such naturally dynamic and collaborative environments. Moreover, incidents involving insider threats could significantly impact FANET operations, where tasks are highly sensitive and essential.

B. Elements of FANET

In the context of FANETs, the inclusion of multiple UAVs and GBSs significantly expands the attack surface. UAVs are susceptible to various threats like signal jamming, physical tampering, and communication interception. Similarly, GBSs, serving as central data collection and command centers, are prone to cyber attacks leading to data tampering, unauthorized access, system interruptions, and potential takeovers. Moreover, the effects of some attacks such as DoS are more accentuated at GBS. Due to their pivotal role in FANETs, GBSs represent an attractive target for attackers seeking to exploit vulnerabilities and gain network control. Furthermore, attackers can exploit out-of-date components, unsafe default configurations, and weak update mechanisms in both UAVs and GBSs. Securing the entire FANET ecosystem and ensuring reliable operation depend on addressing vulnerabilities in UAVs and GBSs, which are constant components.

C. External Entities

The attack surface of FANETs extends further to include various interconnected components and systems such as cloud services, mobile devices, VANETs, IoT devices, edge computing, and other connected devices. When utilizing cloud environments for data processing and storage to overcome UAVs' memory constraints, it's essential to ensure the security and privacy of the data [59] [60]. While edge computing improves real-time processing capabilities by processing data closer to the source of data generation, it also adds more attack points that adversaries might exploit [61]. IoT and mobile devices, offer possible points of exploitation and increase the risk of data manipulation or network compromise [62]. To conclude, additional interconnected components would increase the attack surface overall.

D. Communication channels

Different connectivity channels introduces specific points of interaction that contribute to the overall attack surface. Communication channels and protocols connecting FANET components to one another and to external entities may be the source of attacks. Also, security flaws in the communication protocols in the channel or weak security controls in the implementation of protocols may expose FANETs to vulnerabilities. Additionally, it should be noted that these connected external entities have specific vulnerabilities and call for customized security and communication strategies to ensure the overall integrity and resilience of FANETs.

E. Emerging Technologies

Emerging technologies [63]-[66] such as 5G, 6G, blockchain, artificial intelligence, digital twin are essential for improving communication, trust mechanisms, and decisionmaking in FANETs. 5G represents a significant advancement in wireless communication technology, capable of fulfilling various objectives through the use of existing technologies. Operating as both a user device and a relay, a flying base station might cater to different requirements of various 5G use cases [67]. The innovative utilization of drones for communication during disasters presents an intelligent and creative solution, facilitating effective coordination among first responders and remote cities in crisis zones or conflict areas. However, integrating emerging technologies presents potential security concerns, such as novel attacks and vulnerabilities. These issues might have drastic results in certain applications, such as crisis management. For instance, while digital twins help to enhance security on one hand, it can introduce new security points on the other hand. Moreover, adversarial attacks against artificial intelligence-based systems should be considered. Given FANETs' unique characteristics and challenges, further exploration is needed to grasp and address the complex issues arising from integrating emerging technologies into FANETs and UAVs.

V. TAXONOMY OF ATTACKS BASED ON ATTACK SURFACE ANALYSIS

Attack surface analysis involves identifying and understanding the potential points of vulnerability within UAVs and FANETs, and the taxonomy of attacks further refines this comprehension by grouping related attacks together under the possible entry points identified on the attack surface. In this section, we have chosen to prioritize categories based on their potential impacts, emphasizing those entry points mentioned in the attack surface that could have the most significant consequences in UAVs and FANET. While several categories overlap between the attack surface and the taxonomy of attacks, our focus is on highlighting areas and their related attacks with the highest potential impact. This approach aims to provide a comprehensive yet targeted exploration of vulnerabilities within FANETs, avoiding redundancy in categorization. With this in mind, we provide a comprehensive review of the attacks leveled at UAVs, communication layers and communication architecture in Figure 4.

A. UAV

In this section, our primary emphasis will be on attacks targeting the core elements: UAVs. While GBS are integral to FANETs and share vulnerabilities with UAVs, focusing on UAV vulnerabilities addresses a significant portion of threats against GBS in both hardware and software domains. Yet, specific attacks could notably impact GBS as they represent a single point of failure. Furthermore, it is critical to acknowledge the heightened security measures and greater computing capabilities of GBS, which distinguish them from UAVs. GBS generally offer enhanced computational, storage, and processing capacities, impacting the nature of potential attacks they may encounter. Additionally, the mobility aspect, whether static or dynamic, influences their susceptibility to evading attacks. With this in mind, our focus remains on thoroughly exploring UAV-specific threats, which not only significantly overlap with GBS-related attacks but also underscore the critical vulnerabilities affecting the entire system.

1) Hardware-based Attacks: Hardware attacks are aimed at accessing UAV components during the manufacturing process, or later during maintenance or usage [68], [69]. Components can be tampered with by an attacker installing harmful software or interrupting the flow of data. In addition, an adversary can add external components that will later assume control remotely or capture data. Hardware attacks cause not only loss of control of UAVs, but also critical data can be collected by the attacker. In this section, we summarize the most important attacks in this category in the literature: sidechannel attacks, hardware DoS attacks, battery attacks, and supply chain attacks. Please note that attackers and victims not only aim to malfunction the UAV's hardware through cyberattacks but also cause actual material damage to hardware by way of physical attack. There have been several news reports in the press about UAVs being shot down physically as a form of counteraction [70]-[72].

• Side-channel Attacks

These types of attacks aim to exploit information leaked through physically observable phenomena caused by the execution of tasks in microelectronic components [73]. Most side-channel attacks are conducted without the requirement for any specialized equipment and are therefore difficult to eliminate without impacting upon the UAV system's performance. In [74], side-channel attacks were classified as time-based attacks, power consumption attacks, and electromagnetic radiation attacks. Time-based



Fig. 3. Attack Surface Analysis of UAVs and FANETs

attacks take advantage of the device's operating time [75], whilst power consumption attacks utilize information related to the consumption of the device's battery. Electromagnetic radiation attacks take measurements of the magnetic field around the device while it processes information.

• Battery Attacks

Small drones, which are in high demand for many kinds of tasks, tend to utilize small-sized batteries. While this creates a resource constraint for certain tasks, attackers can also target nodes having small batteries in order to deactivate them from their tasks. Such attacks can cause battery charge to become depleted long before their envisaged time, interrupting connections, triggering mission failures, and even causing UAVs to crash land. These types of attacks can terminate UAV processes that are deemed significant or even critical for flight control whilst exploiting UAV battery components [22]. Moreover, adversaries can also target the charging system used by UAVs. In [76], a battery attack was demonstrated in which that fake requests were sent by attackers to the charging system in order to cause voltage fluctuation problems. It was shown that a *Depletion of Battery (DoB)* attack can consume battery power of a UAV very quickly [77], [78], such as the energy of nodes becoming depleted 18.5% faster under when under attack. Another type of battery attack is a *denial of sleep* attack, which prevents UAVs from entering into sleep mode [79], and thereby continuing to use power unwarrantedly.

• Supply Chain Attacks

Attacks that target the supply chain aim to exploit all kinds of security vulnerabilities that can occur during the procurement phase of UAV components. In [80], a supply chain attack was presented in which 3D design files were remotely modified by attackers to produce faulty UAV components. Another study [81] described a supply chain attack that attempted to add components not specifically designed for the printed circuit board (PCB) that connected various electronic circuit components. However, providing supply chain security is difficult to control due to the large number of manufacturing companies operating within the sector.



Fig. 4. Taxonomy of Attacks Based on Attack Surface Analysis

2) Sensor-based Attacks: UAVs have a variety of sensors that observe events or changes in the environment and collect data to conduct various tasks and in such a way that offers the best level of services. Such sensors are deemed highly attractive to attackers due to the delicate and confidential nature of the information they operate with. Such attacks may even endanger the flight missions of targeted UAVs [30] and at least prevent their efficient operation [29]. A sensor attack performed on gyroscopes was introduced in [82], where audible and ultrasonic noise was applied to 15 different gyroscope sensors in both simulated and real-world experiments. Numerous sensors can be affected by these types of attacks, causing flight balance to be disturbed. In all 20 trials applied within a real-world environment, the target drone lost balance and its flight ended. To further describe sensorbased attacks, we divide them into two categories, spoofing and jamming attacks.

• Spoofing Attacks

In a passive spoofing attack, data is captured and eavesdropped without affecting the UAV system, whilst in an active attack, sensor data is modified or falsified data is introduced. These attacks are generally used to alter previously planned UAV behaviors in order to assume control of the device. The most commonly used spoofing attacks involve GPS spoofing, in which fake GPS data is sent from a malicious device in order to fool the GPS sensor of an operating UAV as shown in Figure 5. This attack was first presented by the University of Texas in 2012 [83]. In [84], fake latitude and longitude information was sent to a GPS unit without disturbing the signals of the original GPS sensor. In another study [85], a GPS spoofing attack was conducted by generating fake GPS data using a device that generates GPS signals and integrated using the SimGen simulation tool [86]. Since sensors cannot detect differences between real and fake data, they transmit all the information they have without question, which may result in UAVs flying off to unintended locations where they could be either damaged or captured. Another study [87] presented GPS attacks with real-world tests shows that the DJI Phantom 3 Standard drone is vulnerable to GPS attacks, which endanger its functioning and control. Attacks on the drone can cause it to depart from its intended flight route, display unpredictable behavior, or even interrupt communication from the remote control.

• Jamming Attacks

Jamming attacks utilize jamming equipment to interrupt sensor signals, hence completely preventing the target UAV from receiving valid sensor information. Since the



Fig. 5. An exemplar GPS spoofing attack

flight control and stabilization of UAVs rely upon stable sensor information, their stabilization systems can be disturbed or even damaged. Although jamming is not effective in all conditions, such as where the jamming signal frequency is inadequate, or where the attacker is excessively distanced from the target, jamming equipment is considered generally available and inexpensive to acquire. An attacker, who was thought to be located near to the test flight area in South Korea, jammed the GPS sensor signals using a jammer which resulted in the UAV crashing into the ground base system, killing an engineer and injuring two remote pilots [68].

3) Software-based Attacks:

• Malware & Backdoor

Attacks that are software-based target the integrity, confidentiality, and availability of the UAV system. Various UAV components could suffer harm in such attacks, including flight displays, navigation systems, or any vital system functions utilized to control and operate the UAV during flights [88]. Moreover, malware can coerce UAVs to navigate towards locations specified by attackers [89]. The initial occurrence of malware infiltrating a UAV without causing direct damage was reported in [90]. The first documented UAV backdoor, named Maldrone [91], employed a Transmission Control Protocol (TCP) connection to gather sensor and driver data, potentially enabling the hijacking of UAV control.

· Zero-Day Attacks

Protecting networks and systems from unauthorized access or potential threats from unknown attacks is a challenging task. The period in which software developers have to fix a publicly disclosed vulnerability is referred to as a "zero-day" [92], [93]. Vendors attempt to deliver a patch or update during this period to address the recently discovered vulnerability. If a patch is not made available as soon as possible, attackers might take advantage of the vulnerability and launch a zero-day attack or leverage from it.

B. Communication Layers

Secure communication is one of the significant requirements for UAVs in order to provide stable, reliable, and secure data transmission and flight control. In this subsection, essential communication attacks are presented in three groups; physical & MAC layer, network layer, and transport layer attacks.

1) Physical & MAC Layer: Radio signals and wireless networks serve as fundamental communication channels between UAVs and GBS, as well as within multi-UAV setups. In [23], the authors demonstrated the disruption of the connection between UAVs and terminals by attacking specific UAV components. Subsequently, they managed to crack the acquired password from a simulated multi-UAV attack. In [94], well-known number of attacks against physical and MAC layers were discussed, including the ARP injection attack, the dictionary attack, and the PTW attack. In another study [95], it was described how an attacker can sniff the signals emitting from UAV devices using Bluetooth. Physical layer attacks are generally classified into two groups: eavesdropping attacks and jamming attacks [96].

• Eavesdropping Attacks

As a type of passive attack, eavesdropping is where a message is captured by an unauthorized attacker. The attacker then violates the network privacy to listen in on the communication without interrupting the transmission [22]. In addition, attackers can elevate an attack by introducing fake messages, delete or modify the intercepted message.

Jamming Attacks

These types of attack aim to disrupt the radio signals used by UAVs by way of introducing pulses and noise. Attackers can utilize powerful transmitters to generate strong signals that disrupt not only the victim's communication, but also all elements of network communication. They can even be be attempted from a remote distance [96]. Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) methods are usually proposed as a means to preventing these types of attack [18]. The fundamental rationale behind these approaches is based on altering the sent frequency values. FHSS is a technique in which signals are quickly switched among various frequency values. Similarly, DSSS changes the frequency value of an original signal by adding noise into a normal frequency signal [97]. There have also been a few proposals [98] aimed at for detecting such attacks in FANETs, and these are discussed later.

2) Network Layer: UAVs communicate with each other or a GBS via an ad hoc network. Differently than traditional networks, ad hoc networks provide communication in the absence of an infrastructure. Further, ad hoc networks reduce the cost and time required to set up a network by eliminating the need for any fixed communication infrastructure. With, nodes in ad hoc networks working collaboratively and benefiting from participation in the network, peers can feasibly join and leave the network at any time without consideration for network dynamics. UAVs are designed to operate with high speed and mobility, and create a flying ad hoc network in order to provide



Fig. 6. An exemplar blackhole attack on AODV

communication within a dynamic network of highly mobile nodes. Since one of the significant advancements reported in the literature occurred at the network layer and new routing protocols introduced for FANETs, attackers also mainly target routing protocols. Attacks at the network layer are aimed especially at controlling network traffic, disrupting routing paths between nodes, as well as accessing data packets and dropping them.

Various classifications have been recommended in the literature for FANET threats and attacks [30], [35]. At the highest level, attacks are divided into active and passive attacks [19]. Passive attacks do not disturb network functionality but sniff out network traffic without modifying communication [99]. Since the functionality of a network remains unaffected by such attacks, it can be challenging to detect passive attacks in networks; necessitating strong encryption mechanisms in order to prevent them. On the other hand, active attacks can be employed to drop, modify, replay, or inject packets, and these can be carried out by either external or internal attackers. Since internal attacks are performed by authorized nodes, their consequences on the network can be more severe in their impact and consequences.

One of the biggest advancements in ad hoc networks has been the development of new protocols and/or improving the existing ones in terms of energy and packet delivery ratio, etc. [19], [100]. However, most of the protocols proposed rely on the cooperativeness of nodes in the network, and fail to propose mechanisms for the purposes of enhancing security. As such, UAVs are vulnerable to routing protocol attacks [19]. A malicious node that aims at disturbing a routing mechanism can decrease the network performance, easily integrating itself into the network and then obtaining critical information [19]. Here, we categorize routing attacks into three groups: attacks on topology, attacks against resources, and attacks could be classified as belonging to more than one group.

Attacks on Topology: Many routing protocols have a route discovery mechanism. In reactive protocols, this mechanism is initiated when a node requests a new route to send packets to a destination. It is vital to secure this mechanism since malicious nodes could exploit it in order to create non-optimal routes between endpoints, and thereby capture data packets. Some of the most significant topology attacks are summarized as follows: a certain destination [101]. If the route is then selected by the source node, all network communication between the source and destination nodes can be eavesdropped by the attacker node, therefore it is referred to as a sinkhole attack [36]. This attack type is generally employed as a first step prior to launching further attacks that will aim to drop and modify data packets.

• Blackhole Attack

The attack type known as a blackhole attack is a combination of sinkhole and dropping attacks. First, the attacker advertises that it has the best route to the required destination, as in a sinkhole attack, and subsequently directs the network traffic to itself. This is followed by other attacks such as modification and packet dropping attacks. Figure 6 illustrates an exemplar blackhole attack launched against the AODV protocol. The source node (S) broadcasts an RREQ message to discover a route to the destination node (D). When the malicious node (M) receives the RREQ message, it sends a fake RREP message to the source node. As can be seen in the Figure 6, M is not located on the shortest path to the destination. However, even if it does not have the shortest or freshest route to the destination, it continues to receive the data packets sent from S to D, and then drops the packets, hence the blackhole effect. A blackhole attack can cause disconnections due to increased network overhead, and the attack can also increase the UAV system's overall energy consumption due to route re-discovery and shorten the lifetime of the network.

Wormhole Attack

This type of attack, known as a wormhole attack [102], sends information as if an attacker is in the neighborhood of other nodes in the network. Hence, genuine nodes start to send their data through the attackers. As shown in Figure 7, in a wormhole attack, attackers create a tunnel between themselves, and then forward the every packets they receive on to other attackers. When attackers gain access to the network, they can perform further attacks such as dropping, altering, and false data injection. In addition, these attacks can damage the proper working of routing protocols as they can prevent discovery of other nodes two hops or further away, resulting in packet loss



Sinkhole Attack

Here, attackers advertise as if they have a better route to Fig. 7. An exemplar wormhole attack on AODV

and network performance reduction.

This attack was first introduced by Hu et al. [103]. Since the tunnel remain invisible to other nodes, wormhole attacks can be difficult to detect. A packet leashing mechanism was presented in [103] to defend against wormhole attacks. A leash is any data added to the packet due to limiting the maximum transmission distance of the packet, and two types of leash were introduced in [103]; geographical leashes and temporal leashes. In addition, a novel routing protocol was designed, called TESLA with Instant Key Disclosure (TIK), which ensures momentary authentication to receiving packets, and TIK prevents further attacks such as replay, spoofing, and wormhole without causing additional overhead. Another solution for UAVs is presented in [104]. The authors proposed a model-driven design method that develops a mathematical model of routing protocols while considering some UAV requirements such as network topology, node mobility, and security needs. Since it allows to compare the hop count given in a packet and the hop count computed based on the traveled distance of this packet, it can detect wormhole attacks.

Rushing Attack

Introduced by Hu et. al. [105], the rushing attack is a type of DoS attack. It was claimed in [105] that this type of attack can be effective against all existing reactive protocols proposed for ad hoc networks such as AODV [106], DSR [107], and even secure protocols such as SAODV [108] and SUCV [109]. The rushing attack exploits the vulnerability of the route discovery mechanism, in which the destination node receives the first RREQ packet and discards the others. When a request packet is received by the malicious node, it is immediately forwarded to the destination node. Since the packet from the malicious node will reach the destination node faster, the destination node will discard other legitimate request packets. As a result, the source node will be forced to use routes containing the attacker node. Many techniques can be employed in order to conduct rushing attacks such as creating wormholes, disregarding MAC or routing layer delays, holding other transfer node queues as full, and sending data at a higher wireless transmission rate [110]. • Route Table Overflow Attacks

• Koule Table Overnow Attacks Even though this attack is not specific to ad hoc networks, it might be more effective on resource-constrained nodes of such networks. In this instance, an attacker sends a large number of route advertisements with the aim of causing an overflow of the routing tables and hereby pre-

this attack type can be more effective in proactive rather than reactive routing protocols [96].
Attacks Against Resources: Attacks in this group aim to increase network traffic and overhead, and thereby slow down data transmission and reduce the network's overall performance. By congesting accessible links, this attack limits the availability of the network and effectively reduce its lifetime. Another effect is to consume nodes and network resources,

venting new routes from being established [110]. Hence,

hence eliminating nodes from further communication, and even creating partitions in the network. Resource-constrained characteristics of nodes make such nodes very attractive for attackers.

· Flooding Attack

The flooding attack can manifest across many different types of implementation, such as by way of sending large numbers of control and data packets. Some routing protocols send Hello packets to one-hop away nodes in order to determine their neighbor nodes. Neighbor nodes receive these messages but do not forward them. The attacker takes advantage of this stage and sends a large number of Hello packets to neighboring nodes. Another type of flooding attack is carried out using the route discovery phase of the AODV routing protocol. This attack, in which a large number of RREQ messages are broadcast at regular intervals, is referred to as the RREQ flooding attacks [36]. These packets can be directed to nodes in the network or to node addresses that do not exist within the network. This attack generally exploits the route discovery mechanism, since the control packets are broadcast in this phase in many reactive routing protocols. In DoB and sleep deprivations attacks, attackers can cause rapid depletion of the battery's charge by sending excessive amounts of data or control packets through the network.

Replay Attacks

This is a DoS attack that re-sends outdated but legitimate data in order to slow down and/or interrupt communication. In [111], well-known DoS attacks such as SYN flooding attacks were implemented by using some tools such as Hping3 [112], LOIC [113], Netwox [114] against a particular UAV (AR.Drone 2.0). It has been observed that the attacks disrupt the communication channels of the drone, resulting in reduced responsiveness, reduced video stream quality, and even a complete loss of control.

Attacks on Traffic: These attacks target the dropping, modifying, forging or replaying of data packets. A malicious node may also then perform additional attacks using the data captured in a prior attack. Some of the more well-known attacks in this group are summarized as follows.

• Dropping Attack

In the dropping attack, an attacker may drop all of the packets that they receive or could selectively drop packets intended for a specific destination. Such attacks, where the attackers solely drop selected certain data packets and forward others is called a *Grayhole Attack* and is more difficult to detect [115]. Attackers may even randomly drop a few packets in order to evade detection; however, in that scenario the effect of the attack on the network might also be limited as well. In general, the attacker node intervenes in the routing protocol during route discovery, as in a sinkhole attack, and places itself within a valid route in order to initiate a dropping attack [116]. Although dropping attacks are covered under the group of attacks on traffic, attackers might also drop routing control packets in order to disrupt the establishment of

valid routes. In such cases, due to restarting the routing discovery mechanism, additional network resources will be consumed as a result.

Sybil Attack

Sybil attack is considered as a form of impersonation attack. Nodes must have original IP addresses in order to join the routing process [19]. However, if the network does not have a central authority node in place to check the identities of nodes in the network, as in most real-life scenarios, attackers can use the address of other nodes or even generate addresses not present in the network. In other words, attacker nodes generate stolen or fabricated identities in attacks referred to as sybil attacks [117]. These sybil nodes perform further attacks such as placing themselves within a route and modifying data packets.

3) Transport Layer: Attacks in this layer are well-known for targeting transport layer protocols, TCP and User Datagram Protocol (UDP), such as SYN (Synchronize) flooding, UDP flooding and session hijacking attacks.

C. Communication Architecture

Communication design is fundamental for establishing a secure and efficient network for FANETs and UAVs, safeguarding against potential threats, and ensuring the integrity of data transmission and control mechanisms. Understanding and addressing these attacks are essential to prevent unauthorized access, data manipulation, and disruptions to the communication flow. Therefore, in this subsection following attacks are discussed.

1) Man-in-the-Middle (MITM) Attacks: When an attacker secretly intercepts and modifies communication between two parties, it is known as a MITM attack allowing unauthorized access to confidential data [118]. MITM attack jeopardize the security and integrity of data transfer and can take many different forms, including packet sniffing, DNS spoofing, and session hijacking. [119] illustrates the impact of unauthorized nodes entering the VANET, such as MiTM attackers that seek to spread and exchange malicious content with the vehicles.

2) Data Tampering Attacks: Attackers could tamper with various data, leading to inaccuracies in critical information such as the UAVs' position, altitude, or direction shared between them and other parties. Tampering with navigation data can misguide UAVs, compromising their situational awareness. Additionally, manipulating sensor data, including environmental sensors or webcams, could distort their view of the environment, further compromising their abilities. Furthermore, altering information related to alarms, emergency circumstances, or safety procedures could impede appropriate reactions or result in false alarms [120].

VI. ATTACK ANALYSIS

One of the main purposes of the current study is to analyze attacks against UAVs and FANETs in particular, and assess their impact on the network. Since one of the main advancements in UAVs' communication happens in the routing layer, specific attacks against a widely used routing protocol, AODV, were analyzed. Initially, a concise overview is presented concerning AODV, 3D Gauss Markov Mobility (GMM), and the four specific attacks in this study. Then simulation results obtained from networks with diverse topologies were demonstrated and meticulously analyzed. The details of the experimentation process are explained in the subsequent subsections.

A. Routing Protocol: AODV

AODV is one of the most used reactive routing protocols in ad hoc networks. Within the current study, AODV was chosen over alternative protocols due to its widespread adoption, simplicity in implementation, and minimal operational overhead [121].

In AODV, when a node needs to send data to a destination, it checks for an existing route in its routing table. If absent, a route request (RREQ) is broadcasted, prompting nodes with a valid route to reply with a route reply (RREP). The source node then selects the most refresh and shortest route based on maximum sequence number and minimum hop count. Once established, data transfer commences. To handle link breakages caused by mobility, AODV utilizes route error packets (RERR) to notify nodes, allowing affected nodes to trigger route discovery mechanism for alternative routes, ensuring robustness in dynamic ad hoc networks.

B. Mobility Models: 3D GMM

3D GMM is a memory-based model with a single parameter that could potentially address the need for a realistic mobility model capable of adjusting various degrees of randomness [122]. The model is applied as a time-based mobility model specifically to avoid abrupt changes in the direction or velocity of UAVs. By utilizing this model, it becomes feasible to simulate various real applications seamlessly while accommodating 3D movement in UAVs [55]. To maintain meaningful consecutive positions, the model stores prior node movements in memory and utilizes the parameter α (ranging between 0 and 1) to govern subsequent node mobility behaviors [123].

C. Implementation of Attacks

In the current study's analysis, the following four attacks against AODV were implemented in realistic simulation scenarios: sinkhole, dropping, blackhole, and flooding attacks.

1) Sinkhole Attacks: In this implementation, when the attacker node receives a RREQ packet, it sends a fake RREP packet in return. The fake RREP packet contains a higher destination sequence number than the current one; hence, if the RREP packet reached the source node, it is guaranteed to be selected as the route to the destination. Moreover, it claims itself as being one hop away from the destination node.

2) Dropping Attacks: In this attack implementation, if the attacker node is deemed to be located on the active route between the source node and the destination node, it drops every data packet it receives and thereby prevents communication between these endpoints. However, since malicious nodes are selected randomly, there is no guarantee that they are even located on active routes. In such cases, the effect of an attack on the network would be limited. *3) Blackhole Attacks:* This attack is a composite attack that includes both sinkhole and dropping attacks. In other words, the attacker node first places itself in a route, then drops data packets that are transmitted thorough that route.

4) Flooding Attacks: This exploits a vulnerability in the route discovery mechanism. An attacker node sends a significant number of RREQ packets to randomly selected nodes in the network. In the simulations, a destination node is selected randomly, and then 10 sequential RREQ messages are broadcast for this destination node. The attack is repeated every 3 seconds for the duration of the simulation.

TABLE V SIMULATION PARAMETERS

Parameters	Values
Routing protocol	AODV
MAC protocol	IEEE 802.11b
Simulation time	1800 seconds
Area	12000 m x 12000 m x 300 m
Number of nodes	25, 50
Node speed	720 km/h
Transmission range	250 m
Traffic type	UDP
Packet size	512 bytes
Packet count	1/s
Bandwidth	11 Mbps
Ratio of malicious node	no attack, 5%, 10%, 15%, 20%, 25%
Mobility model	3D GMM Model
Bounds for GMM	X: [0; 12000], Y: [0; 12000], Z: [0; 300]
α for GMM	[0.25-0.7]

D. Simulation Parameters

In this study, attacks were simulated using the ns-3 simulation tool [124]. The simulations contain 25 and 50 nodes in order to assess the effects of node density on the network performance. A specific immobile node designated as the GBS is located at the center of the simulation area. Ten network communications are built by randomly assigning 10 source and 10 destination nodes. The remaining nodes may function as relays nodes. The destination nodes are responsible for collecting data from other nodes and send it to the GBS. The communication between destination nodes and the GBS starts at the 10th second and continues until the end of the simulation. Attacker nodes, selected randomly from nodes excluding the source and destination, and remain constant for each attacker ratio (ranging from 5% to 25%), despite changes in the type of attack implemented.

In the first stage, a number of different network topologies are selected and results are subsequently obtained without any attack. Subsequently, various types of attacks (blackhole, sinkhole, dropping, and flooding attacks) are individually simulated on these chosen network topologies. Specifically, 10 simulations are executed without any attack, and for each attack type, 10 simulations are conducted for each of the 5 attacker ratios (between 5% and 25%), totaling 210 simulations. The average performance result was then used in the following attack analysis.

3D GMM was used to simulate 3D natural flight of UAVs within a realistic approach as shown in [125]. The alpha

parameter value of 3D GMM, which was used to provide randomness and predictable balance of the UAV's mobility was initially set as 0.25 and then increased incrementally by 0.05 in order to create different network topologies. The simulation parameters applied are summarized in Table V. Our previous study [36] was extended with additional simulations in which the UAVs move within a larger area and with more nodes over a longer simulation times. Moreover, more realistic scenarios were implemented. For example, while all nodes were sending their data to one mobile server in the previous study, here nodes can communicate with each other and send the collected to the stationary GBS which is located in the center of the simulation area.

E. Experimental Results

In this subsection, we present and examine our experimental findings, focusing on the network's performance under diverse attack scenarios. The following performance metrics were used to evaluate the performance of networks under attack. Packet delivery ratio (PDR) is the average ratio of the total number of packets received by all nodes in the network to the total number of packets sent to the same nodes. End-to-end (E2E) latency is the measurement, in seconds, of the average of all delays that occur on the network during data transmission between end communication points. Overhead is the ratio of the total control packets generated by the routing protocol and received by the nodes to the total number of data packets received. Under simulated blackhole, sinkhole, dropping, and flooding attacks across different attacker ratios (ranging from 5% to 25%), the network's resilience and performance were observed. The avarage performance metrics derived from simulations involving 25 and 50 nodes are presented in Table VI to Table X.

TABLE VI EFFECTS OF SINKHOLE ATTACK

	A 1			
	Attacker	PDR	F2F(s)	Overhead
	ratios	TDK	L2L (3)	Overnead
~	0%	93.70%	0.084	7.40
sity	5%	93.70%	0.097	7.69
en	10%	93.60%	0.102	8.16
Ą	15%	93.50%	0.107	8.42
MO	20%	93.60%	0.106	8.68
Г	25%	93.60 %	0.109	9.29
4	0%	94.00%	0.100	3.77
sit	5%	93.40%	0.117	4.36
en	10%	94.00%	0.139	4.93
D	15%	94.00%	0.149	4.90
igt	20%	94.00%	0.162	5.96
H	25%	94.00%	0.174	6.23
	1			

Sinkhole Attack: The attacker node attempts to divert or attract network traffic towards itself. As shown in Table VI, while the PDR value is high in a network without any attack present, the PDR value can decreases when the attackers join the network. However there are several cases which might decrease the impact of the attack. For instance, if the attacker node is already located on a route between the source and destination node, and the target node is physically only one

hop away from the attacker which is mostly possible in a high dynamic topology, the impact of the attack might be somewhat restricted. Here, the attack does not alter even the length of the existing active route.

In another scenario, attackers could prompt the establishment of an alternative, albeit longer, route that still provide packet forwarding to the destination. Therefore, the noticeable increase in delay times during this attack highlights that packets are being forwarded along a longer alternative route instead of the shortest available path. Moreover, randomly selected malicious nodes may not attract data packets and it may not have as much impact as thought due to FANETs' dynamic topology. Although PDR may appear unchanged during the ongoing attack, the attack still modifies the network's behavior, leading to indirect impacts. When this attack is initiated initially and combined with another attack, it has the potential to amplify its impact on the network, as demonstrated in consecutive analyses.

With an increase in the attacker ratio, the E2E latency also rises, as previously noted, potentially due to the establishment of longer alternative routes. During network attacks, the presence of invalid active routes and disrupted node connections resulted in the broadcasting of control messages or initiated route discovery mechanisms. Consequently, as the network experienced a higher volume of control packets, the observed overhead increases.

TABLE VII EFFECTS OF DROPPING ATTACK

	Attacker ratios	PDR	E2E (s)	Overhead
~	0%	93.70%	0.084	7.49
sit	5%	93.68%	0.083	7.41
en	10%	93.00%	0.082	7.43
Q	15%	93.00%	0.080	7.43
MO	20%	92.8%	0.080	7.49
Г	25%	92.42%	0,080	7,49
>	0%	94.00%	0.100	3.77
sit	5%	93.60%	0.090	3.67
en	10%	93.50%	0.088	3.67
High D	15%	93.40%	0.087	3.63
	20%	92.68%	0.086	3.59
	25%	93.80%	0.094	3.62

Dropping Attacks: In this type of attack, the attacker node drops the data packets it received during simulation time. Two possible scenarios are exist for this attack: one involving randomly selected attackers which might not be on any route and another focusing on attackers specifically selected among nodes on the active route. Since the attacker node can only receive data packets if it is located on an active route, we expect that the attack will be more effective in the second scenario. As seen in Table VII, for the first scenario, the attack's impact is limited to certain communication routes, resulting in localized disruption rather than significantly impairing the overall functionality or availability of the entire network. Moreover, an increase in the total number of attacker nodes doesn't necessarily significantly raise the probability of these nodes being located on active routes in a highdensity network. Therefore, the impact of an attack with a higher attacker ratio might still be limited on PDR, potentially

TABLE VIII EFFECTS OF DROPPING ATTACK WITH SELECTED ATTACKERS ON ACTIVE ROUTES

	Attacker ratios	PDR	E2E (s)	Overhead
~	0%	93.70%	0.084	7.49
sity	5%	92.8%	0.084	7.49
en	10%	92.6%	0.083	7.49
٩ ب	15%	91.7%	0.078	7.53
Ň	20%	90.74%	0.075	7.66
	25%	89.6%	0.073	7.71
~	0%	94.00%	0.100	3.77
sit.	5%	92.8%	0.087	3.78
en	10%	91.6%	0.089	3.79
1 1	15%	90.1%	0.089	3.84
lgi	20%	88.3%	0.089	4.09
ΗΞ	25%	84.6%	0.083	4.21

The average metrics after simulating the second scenario are as shown in Table VIII. When a dropping attack occurs on active routes within a network, the consequences for network performance can be profound. The attacker disrupts the data flow, causing a noticeable decline in the PDR by approximately 4% in low-density networks and up to 10% in high-density networks. In high-density networks, as the number of attackers increases, their probability of settling on active routes also increases, consequently leading to the observed lower PDR. Please note that while attackers are initially chosen on active routes, this selection might change throughout the simulation due to mobility. As shown and expected, the position of attacker nodes is highly critical for the impact of this attack. Moreover, failure to transmit packets from the source node to the destination node increased the overhead by increasing the number of control messages in the network. On the other hand, since the number of data packets that reach the destination under attack decreases, E2E decreases.

TABLE IX EFFECTS OF BLACKHOLE ATTACK

	Attacker	DDD	E2E (-)	Orienteed
	ratios	PDR	E2E(s)	Overnead
~	0%	93.70%	0.084	7.49
sit	5%	87.00%	0.073	8.34
en	10%	83.50%	0.070	9.07
Ω.	15%	81.50%	0.066	9.63
No.	20%	80.70%	0.061	10.14
	25%	79.10%	0.056	10.89
~	0%	94.00%	0.100	3.77
sit.	5%	83.50%	0.117	4.37
en	10%	79.00%	0.066	5.66
igh D	15%	78.71%	0.068	6.26
	20%	77.00%	0.073	7.175
H	25%	76.00%	0.070	7,693

Blackhole Attack: Blackhole attack poses a major threat to the performance and reliability of FANETs, as evidenced by the results presented in Table IX. This composite attack, comprising both sinkhole and dropping attack respectively, deceitfully attract and then drop data packets, causing substantial disruptions in network functionality. Resulting in a

sharp decline in essential performance metrics such as PDR, leading to a decrease of up to 15% in low-density networks and approximately 18% in high-density networks.

As the number of attackers increased on the network, the blackhole attack proved more effective than solely applying either the sinkhole or dropping attacks. Furthermore, in networks with a high volume of malicious nodes, increased overhead intensified network congestion and depleted vital resources. The consequent decrease in the number of packets reaching their destinations resulted in an overall reduction in end-to-end efficiency.

TABLE X EFFECTS OF FLOODING ATTACK

	Attacker ratios	PDR	E2E (s)	Overhead
~	0%	93.70%	0.084	7.49
sity	5%	92.66%	0.141	15.48
en	10%	91.40%	0.134	15.94
Q	15%	90.47%	0.138	16.02
MO	20%	86.30%	0.138	16.09
Г	25%	84.45%	0.139	16.27
>	0%	94.00%	0.100	3.77
sit	5%	92.33%	0.099	4.91
ı Den	10%	89.00%	0.183	8.14
	15%	85.60%	0.184	8.12
igh	20%	76.30%	0.175	8.14
Η	25%	62.70%	0.172	8.11

Flooding Attack: In a flooding attack, a form of DoS attack, the RREQ control packets are incessantly broadcasted, aiming to overwhelm the network by transmitting 10 RREQ messages every 3 seconds. This repeated transmission is intended to exhaust network resources and deliberately induce network congestion, disrupting normal operations and impeding the network's ability to efficiently process legitimate data packets. Legitimate nodes, bombarded with excessive number of RREQ messages, encounter significant decline in the PDR as presented in Table X. The rise in the number of attackers in both high-density and low-density networks correlates with a substantial decrease in the PDR.

In low-density networks, while the attack has an impact on performance, the effects might be comparatively less severe due to the sparser node distribution. However, flooding attacks exert a pronounced impact on high-density networks, exacerbating congestion and severely compromising network performance, resulting in a reduction of up to 31%. Moreover, the excessive transmission of RREQ messages intensifying increased the network overhead to almost more than double, thereby creating a bottleneck. This bottleneck leads to significant increases in E2E metrics, differentiating it from other attacks and hindering the timely delivery of remaining data across the network.

General Discussions: The effects of all attacks on PDR are comparatively illustrated in Figure 8. Sinkhole and dropping attacks, conducted by randomly selected attackers, seem to exert minimal impact on network performance. Indeed, in the case of a sinkhole attack, the primary objective is to deceive network nodes by providing false routing information and redirecting traffic through malicious nodes. These attacks aim to mislead rather than directly interfere with data packets, potentially resulting in their impact being less pronounced compared to other attacks. Similarly, dropping attacks attempted by randomly chosen attackers might indeed have a limited impact on network performance due to their positional constraints within the network. On the other hand, deliberate placement of attackers on active routes in dropping attacks allows them to strategically receive and drop packets passing through these active routes. This interference significantly disrupts the transmission process, leading to a reduction in PDR. The contrast between these two scenarios underscores the pivotal role of attackers' placement within a highly dynamic network.



Fig. 8. Comparison of PDR on networks under different attack types

The blackhole attack combines characteristics from sinkhole and dropping attacks, posing a significant threat to network security. This unique combination enables the blackhole attack to profoundly impact network performance, especially evident when the attacker ratio reaches 25%. This scenario notably decreases PDR, signifying the attack's substantial hindrance to successful data transmission within the network.

Conversely, flooding attacks create severe traffic congestion by flooding the network with frequent RREQ control messages, leading to dropped data packets before reaching their destinations. Notorious for consuming substantial network resources, flooding attacks prove to be the most impactful, resulting in a staggering reduction in PDR of up to 62%. It is also important to note that the effect of all attacks is directly related to their specific parameters.

Figure 9 demonstrates a notable increase in the E2E delay when the network is not under attack, compared to instances with active sinkhole and flooding attacks. The sinkhole attack prolonged packet delivery times by rerouting packets through attackers, establishing alternative routes that deviated from the shortest paths. These detours caused delays in package delivery as the alternative routes were less efficient, consequently prolonging the overall delivery time. A distinctly different scenario was observed in flooding attacks, where an escalation in attacker ratio notably increased the volume of control packets. This surge in control packets, alongside an increase in dropped packets, led to traffic congestion, contributing to delays in delivering packets intended for their destinations.

The E2E delay is directly calculated based on the number of successfully delivered packets, hence closely connected with



Fig. 9. Comparison of E2E on networks under different attack types

PDR. Consequently, dropping attacks executed by attackers positioned on active routes and blackhole attacks significantly reduced the number of delivered packets, resulting in notably lower the E2E delays. However, dropping attacks employing randomly chosen attackers exhibited a limited effect on delay, causing only slight fluctuations in the E2E delay. The inefficiency of these attacks, particularly in terms of dropping packets, had a negligible impact on the overall packet transmission time, demonstrating their limited effectiveness as an associated factor.



Fig. 10. Comparison of overhead on networks under different attack types

As the number of attackers on the network increased, the overhead also escalated due to the re-initiated route discovery mechanism and error messages, as depicted in Figure 10. This rise was observed as highly significant for all attack types, as anticipated. Notably, in the case of flooding attacks, the overhead was considerably higher compared to other attacks. This was primarily due to the periodic broadcasting of RREQ packets by the malicious node, alongside numerous other control packets, resulting in an excessive volume of network traffic.

This study pioneers a comprehensive analysis of attacks in FANETs, using realistic parameters. Simulations with 25 and 50 nodes demonstrated that in high-density networks with attacker ratios of 10% and 20%, PDR dropped below 80% for blackhole and flooding attacks respectively, with relatively lower impact on low-density networks. High density fosters node cooperation, aiding attackers in disrupting the network. Furthermore, as the node intensity decreased in the network, the results of different attack types were seen to converge. Blackhole and flooding attacks in high-density networks reduced PDR by over 15%, with flooding attacks proving notably more effective.

VII. COUNTERMEASURES

The previous section highlighted how attackers can significantly hinder network performance by disrupting routing mechanisms, causing packet loss, and creating congestion, and hence adversely impact UAV missions. Consequently, researchers are actively developing solutions focusing on prevention and detection. We believe this analysis will expedite research efforts aimed at enhancing the security of FANETs.

The first line of defense for UAV systems is referred to as prevention, with the aim being to prevent an attack from entering the system at all. These preventative measures are provided through traditional methods such as authentication, encryption, and secure routing protocols. However there is often a trade-off to be managed between the added security and availability of the system being protected. Moreover, insider threats are always a possibility. Therefore, detection, as the other form of countermeasure, aims to monitor the system and to detect anomalies and attacks. This second line of defense is an unavoidable component part of the security structure. In the subsequent subsections, an overview is presented of the countermeasures proposed in the literature for FANETs and networks of UAVs.

A. Prevention

A significant part of the research published on FANETs has been on developing efficient and suitable routing protocols for these dynamic systems. However these routing protocols are generally not designed with security in mind, and the effects of attacks against routing protocols can be significant and even critical where networks are partitioned and communication interrupted. When a routing protocol is targeted by attackers, not only does it have to continue providing its service, but it should also maintain effective levels of performance and efficiency [19]. Therefore, some studies have proposed securing routing protocols. However, due to the hardware limitations of UAVs, researchers are working on developing lightweight solutions. The proposed solutions in this section are categorized into four groups: authentication mechanisms, blockchain-based solutions, physical layer security, and other proposals presented for specific attacks.

1) Authentication Mechanisms: The authentication protocol stands as a fundamental security measure within distributed systems, aiming to uphold the integrity and trustworthiness of nodes during communication. In [126], a lightweight mutual authentication mechanism was presented that aimed to ensure secure communication between UAVs and the base station. The fundamental principle of the proposed mechanism was that UAVs and GBS employ a challenge-response combination of physical unclonable function as the initial condition of a chaotic system in order to randomly mix the message, which

carries a seed to produce a secret session key. The simulation presented consisted of three nodes (UAV, server, and user), and was conducted using OMNeT++ [127]. It was shown that the mechanism outperformed the acclaimed cryptographic proposal [128] in terms of computing cost, communication overhead, and energy consumption.

Mallikarachchi et al. [129] delves into the condensation of data frame payloads through compression and data hiding, aiming to authenticate the payload of data frames received by nodes in a FANET. The primary objective is to verify the integrity of each received packet along the communication path. The key contribution of this research lies in the design of a payload authentication scheme that combines masking (XOR), a lossless compression technique, and data hiding. In order to ensure the lightweight and energy-efficient nature of the scheme, a straightforward XOR operation is employed, coupled with image generation and JBIG2 compression to generate the bitstream embedded into the CP. Upon reception, the hidden data is extracted and decoded, allowing for a comparison against the payload of the received data frame. The evaluation of the proposed scheme, in terms of bit error rate, revealed BERs of less than 0.7×10^{-4} , aided by the implementation of a 7-bit Hamming code. Furthermore, experiment results affirm the proposed scheme's capability to localize tampered data frames. The validation of the scheme is conducted using a simulated FANET model implemented in MATLAB 2018b, featuring a 3D Random Waypoint (RWP) mobility model with the AODV routing protocol.

In [130] the design of a robust and lightweight authentication and key agreement scheme for cloud-assisted unmanned aerial vehicles using blockchain in FANET (LAKA-UAV) is introduced. The primary aim in this study is to ensure integrity and decentralization functionalities for data sharing for cloud-assisted UAVs in FANETs. LAKA-UAV leverages cloud technology to attain ample storage resources and computing capabilities. Within each block, only metadata is stored to enhance block construction and minimize distributed storage waste. Additionally, LAKA-UAV employs blockchain technology, specifically Hyperledger Fabric, to guarantee efficient access control, data integrity, and decentralization through log transactions. Through testbed experiments and blockchain implementation, LAKA-UAV demonstrates efficient computation cost and a high-security level. While LAKA-UAV incurs a higher communication cost than comparable schemes, it ensures lightweight computation and storage costs, along with superior security features compared to existing schemes.

Wu et al. [131] proposed an improved version of the threeparty authentication protocol given in [132] in order to protect an Internet-of-drones (IoD) environment from known security threats. The improved protocol consisted of three phases: drone registration, user registration, and login authentication. While an adversary could collect stored data from the server, intercept the messages in the public channel, and draw out data from a captured UAV, as shown in [132], the improved version introduced in [131] addressed these vulnerabilities.

In [133], an improved and secure access control system that utilized certificates initially registered by a trusted authority was presented for IoT-enabled drone environments. The mechanism provided key agreement and mutual authenticity among drones, and also between drones and the ground station. The proposed system completed the access control procedure by exchanging just two messages. The proposal was claimed to be robust to known threats such as MITM attacks, physical attacks, forgery attacks, privileged insider attacks, replay attacks, and session-specific temporary information threats.

2) Blockchain-based Solutions: Another point to consider is to secure drone communication during data collection and transmission while preserving the integrity of collected data. Blockchain is considered as a solution to data integrity and privacy problem ensuring a safe and trusted communication and implemented to ad-hoc networks [134]–[138]. Blockchain uses cryptographic algorithms to secure transactions and prevent unauthorized access. This can help to protect sensitive data in FANETs, such as mission-critical information or personal data of individuals involved in the operation. Through blockchain, transparent record of all transactions on the network can help to increase accountability and trust among participants in FANETs.

[138] proposes employing blockchain technology to improve security with private key cryptography. In the paper, the benefits of blockchain are emphasized, including its distributed nature and immutability, which offer a safe way for controllers and drones to communicate. In order to increase security, timestamping and GPS are used in conjunction with data encryption between the UAV and control panel and data hashing for the cloud. In addition to UAVs, the study proposes a decentralized blockchain-based solution with potential applications across other industries.

3) Physical-Layer Security (PLS): Securing UAV communication encounters challenges due to inherent resource limitations, rendering traditional cryptography impractical. Employing Physical-Layer Security (PLS) in UAVs offers secure information-theoretic transmissions [139] with minimal computational complexity, addressing energy, computational, and memory constraints [140].

In [20], prevention methods for PLS are extensively discussed. For instance, the *Noise-Aided PHY Security* method intentionally degrades an eavesdropper's channel by introducing fabricated noise into information transmissions [141]. Its objectives include reducing the Secrecy Outage Probability (SOP), increasing system throughput, and enhancing ergodic secrecy capacity [142] to bolster secrecy functionality.

Another approach, *cooperative jamming-aided PHY security* [143] [144], involves a UAV transmitting both data and a jamming signal to deter eavesdroppers. Self-interference cancellation helps the intended receiver filter out the jamming noise. Objectives here include minimizing SOP [145], improving system throughput, and enhancing ergodic secrecy capacity.

Incorporating Line-of-Sight (LoS) links and utilizing multiple UAVs strategically for cooperative jamming [146] necessitates meticulous trajectory planning to prevent collisions. The *Legitimate Eavesdropping Aided PHY-Security* approach leverages the receiver's null space to interfere with the eavesdropper's link. Here, a UAV mimicking an attacker emits jamming signals to disrupt dubious users. Authorized receivers utilize self-interference cancellation to filter unwanted signals. However there are some issues to be considered [147] [148] such as aerial to ground or aerial to aerial channel planning, precise Channel State Information estimation, and cooperative tactics using UAVs for enhanced covertness and covert data transfer.

4) Other Proposals for Particular UAV Attacks: There have also been proposals [82] [149] aimed at preventing attacks against UAV sensors. In real-world applications, optical flow sensors initially require a feature detection algorithm in order to pinpoint areas of the ground plane image that are especially conducive to tracking. The adversary can simply exploit environmental settings such as covering the flight area to interrupt the vision of the optical flow camera, alter the plausible inputs to affect the sensors input, or create valuable input for the sensor system by utilizing knowledge of the optical flow algorithm.

In [149], a more robust optical flow algorithm was proposed to prevent spoofing attacks on the downward-facing optical flow camera sensors, which provide stabilization to UAVs during flight. In [82], a noise attack against a gyroscope was performed and the possibility of an attacker utilizing deliberate sound noise to damage UAVs with Micro-Electro-Mechanical Systems (MEMS) gyroscopes was explored. Real-world attack tests revealed that in each of the 20 attack test trials, one of the two target UAVs with weak gyroscopes was shown to malfunction, and crash-land soon after the attack had been initiated. Recommended prevention methods include hardware modifications such as physical isolation from the attacker sound noise, differential comparator, and resonance tuning.

Li et al. [150] proposed a lightweight digital signature protocol in order to prevent MITM attacks, in which malicious nodes eavesdrop on communications between UAVs and GBS by posing as the GBS and sending falsified commands in order to jeopardize a UAV mission. The chaotic complex system employed by the GBS in the proposed protocol allows it to construct a digital signature based on the command message, which it then appends to the command message. The UAV then verifies the digital signature prior to executing the command it received by comparing it to the digital signature produced from the command message itself. If the verification of the digital signature is not proven, the request is instantly denied, and the Return-to-Launch (RTL) mode is initiated, forcing the UAV to return to its takeoff position.

Some countermeasures are proposed for the three wellknown attacks, DoS, BufferOverflow, and ARP Cache Poisoning, in [151]. *Watchdog timer* being first method involves adding a hardware device that monitors and resets the system if it detects any malfunction or abnormal behavior to limit the time the CPU can be used for non-navigational processing. The other method *hardline input data filtering* approach involves setting up filters on the input data to block any unwanted or malicious data from entering the UAV's embedded system. Another method *anti-spoofing mechanisms* is added to the UAV's access point to prevent attackers from impersonating legitimate access points and intercepting or modifying data sent between the UAV and the GBS.

General Discussions: The proposed prevention approaches are summarized in Table XI. In conclusion, it is imperative to

design systems equipped with defenses to thwart attacks that could potentially harm UAVs and FANETs. Attack prevention often involves enhancing UAV or FANET components to render attacks impractical or dysfunctional, as well as implementing effective preventative measures capable of withstanding potential threats.

UAVs have become a crucial component of the communication networks that connect cellular clusters to various infrastructures including IoT and VANET. UAVs have the potential to function as aerial ground stations, relay nodes, and infrastructure in remote regions within the realm of wireless communication systems. Despite considerable research progress, numerous challenges persist on physical layer security such as data interception and jamming which pose more formidable challenges than conventional terrestrial eavesdropping. Hence, there is a need to explore advanced techniques within the realm of physical layer security to fortify defenses against attackers.

In FANETs, routing protocols are essential; however, many of these protocols were originally designed with insufficient security consideration. Additionally, several studied protocols for FANETs are primarily designed for ad hoc networks in general, without specifically addressing FANETs' unique requirements. Limited research has been conducted on the security aspects of FANET routing protocols, posing a considerable danger that attackers could potentially take control of the network or interfere with its normal operations due to the vulnerability of these protocols to attacks.

Additionally, it is crucial to delve into privacy and integrity concerns associated with UAV-collected data in the light of addressed FANET-UAV challenges. Adopting cryptographic techniques for UAV systems or FANETs, either for authentication, access control, privacy, confidentiality or trust establishment, require some form of trade-off in terms of computational cost and energy limitations, network bandwidth consumption, and potential latency on the chip. Leveraging blockchain-based solutions within FANETs can strengthen prevention systems through the establishment of transparent and tamper-proof records for transactions and communications. However, it is expected that certain security, safety, and privacy measures should be enforced and subjected to thorough research considering the unique challenges faced by UAVs and FANETs. Exploring distributed and collaborative prevention mechanisms within the FANET framework is vital stands out as critical research areas within the prevention paradigm. Last but not the least, evaluations of the proposals are very limited as shown in Table XI.

B. Detection

Prevention techniques are effective against known attacks; however, they may not always prevent new types of attacks or insider threats. Therefore, detection systems are essential complements, aiming to identify attacks that evade existing prevention mechanisms. Intrusion detection systems (IDSs) play a crucial role in detecting threats before compromising a system's integrity, confidentiality, or availability, striving to minimize inflicted damage. This section categorizes proposed studies on intrusion detection based on their detection

 TABLE XI

 Outline of the prevention solutions on UAVs' security

Reference	Year	Method	Dataset	Attacks	Simulations
[149]	2016	Novel Algorithm Proposed	No dataset	Sensor Input Spoofing	No sim., Burrows-Abadi- Needham (BAN) logic analysis [152]
[150]	2020	Digital Signature Protocol	No dataset	MITM	Customized Sim. Framework
[126]	2020	Mutual Auth. Protocol	No dataset	Cloning, MITM, Replay, Tampering	OMNeT++
[133]	2020	GCACS-IoD	No dataset	Drone Impersonation, Session Key Disclosure, Physical Capture	No sim., ROR Model Analysis [153]
[131]	2022	Enhanced Auth. Protocol	No dataset	Privileged Insider, MITM, Replay, Physical Capture	No sim., ROR Model Analysis [153]
[132]	2022	Mutual Auth. Protocol	No dataset	Replay, Impersonation, Brute Force, DoS , MITM	No sim., Burrows-Abadi- Needham (BAN) logic analysis [152]
[129]	2023	Auth. Scheme	No dataset	Eavesdropping, MITM	MATLAB 2018b, Bit error rate analy- sis
[130]	2023	Lightweight auth. and key agreement scheme	No dataset	Replay, Impersonation, Session key disclosure, Desynchronization, Ephemeral secret leakage (ESL), Off-line password guessing, MITM	ROR oracle model [154], AVISPA [155]

methods, encompassing signature-based, anomaly-based, and specification-based approaches.

1) Signature-based IDSs: These systems rely on employing signatures, rules, or patterns that define known attacks. While highly effective and efficient against known threats, they are primarily favored in commercial systems. However, their limitation lies in their inability to detect novel, unknown attacks or newly evolved variations of known attack patterns. Additionally, these systems require regular updates to their signature databases to remain effective.

A rule-based study inspired from the human immune system (HIS) is given in [156]. The study consists of three phases. In phase 1, safe routes between source and destination are identified by using consecutive Hello packets. These selected secure routes progress to Stage 2. In Phase 2, they use reverse test packets sent from the destination to the source to find potential malicious UAVs among the intermediary nodes. This method relies on spotting differences in the packets for detection. Routes free from flagged malicious nodes move to Phase 3 for thorough robustness checks. This phase assesses hop count, Round Trip Time (RTT), and Signal Strength Intensity (SSI) as evaluation criteria. Routes with fewer hops, shorter RTT, and stronger signal take precedence for safety. The proposed approach effectively identifies blackhole, sinkhole, wormhole, and fake information dissemination attacks. However, the increased communication between source and destination endpoints might lead to added overhead. The authors expand on their study by introducing decision-making agent defense agents in [157]. The UAV designated as the defense agent replicates itself near UAVs on suspicious routes and transmits test packets.

Another study that use Hello packets to identify secure routes is given in [158]. A recent study [159] uses both a rulebased approach and a mobile agent-based negotiation process. In the initial phase, the system employs specific rules and principles, analyzing various aspects such as node behavior, data transmission patterns, route response messages, sequence numbers, and hop counts to detect potentially malicious UAVs. This phase also involves the investigation of node activities and interactions among neighboring nodes to identify anomalies or suspicious behavior. In the second phase, certain designated nodes function as agents, selected randomly to facilitate data transmission between source and destination UAVs. These agents play a crucial role in discovering neighbour UAVs within a one-hop distance. Furthermore, they employ a hash function to secure information from potential adversarial UAVs within the communication network. To ensure security, these agents generate digital signatures for any information exchanged between source and destination UAVs. The system demonstrates heightened residual energy and packet delivery ratio while maintaining lower levels of false positives.

A traditional approach for detecting jamming attacks was proposed by [98], in which a detection framework monitors the signal power density of each device, compares it with the signal strength of that device, and executes intrusion detection and prevention mechanisms. Another study [160] presented a novel lightweight distributed rule-based detection approach called Lids in order to detect flooding attacks. Lids limits the packets drones can send within set time frames, verified by shared transmission data among drones. This method efficiently prevents flooding attacks by swiftly neutralizing adversary drones. But it poses challenges of potential network congestion and increased drone energy consumption, notably impacting small-sized UAVs.

2) Anomaly-based IDSs: The system creates a profile of normal behavior and flags any activities deviating from this pattern as anomalies, potentially indicating an attack. These methods are good at detecting new attack types. However, defining what constitutes normal behavior poses a challenge, especially as it can evolve over time. Consequently, this approach might generate a significant number of false positives. Anomaly detection employs various techniques, including statistical-based and machine learning-based approaches.

Traditional Machine Learning-based Studies: A recent study [161] proposes a machine learning-based (ML) approach to detect various attacks like hijacking, GPS signal jamming, and DoS attacks targeting drones in smart cities. The study applies several classification algorithms, including Support Vector Machines (SVM), Naive Bayes (NB), Linear Regression (LR), and Random Forest (RF), using data from the DJI Phantom 4 drone dataset [162]. This dataset comprises GPS, gyro, and power data collected from a single drone. While the aim is to bolster drone system security against potential threats, forming a comprehensive security strategy solely based on data from a single drone presents challenges.

In [163], a study on detecting GPS spoofing attacks is presented. The study introduces the UAV attack dataset, utilizing logs that collect sensor data including GPS, accelerometers, and gyroscopes during flight. However, it is limited by the use of only a few drones and a restricted sensor set. Similarly, in [163], the authors introduced an anomaly-based approach for detecting GPS spoofing attack. This approach allows for the use of logs that collect sensor data, such as GPS data, accelerometers, and gyroscopes during flight, to create a dataset for training. The results of the approach show that it achieves high F1 scores of 99.56% and 99.73% for benign and malicious sensor readings, respectively, indicating its effectiveness in detecting GPS spoofing attacks.

Another recent study [164] employed ML to detect DoS attacks within UAV networks. Utilizing the AWID2 dataset [165], the study implemented gradient boosting techniques such as XGBoost, CatBoost, and LightGBM to train a model. Real drone testing followed the model's training. Notably, LightGBM demonstrated superior performance in Area Under the Curve (AUC) metrics and training time among these algorithms. However, the AWID2 dataset, derived from a typical Small Office/Home Office (SOHO) network infrastructure, lacks the capacity to effectively model the complex behaviors and mobility inherent in UAV operations. To further refine the model's effectiveness, the study applied Bayesian optimization specifically to LightGBM for hyperparameter tuning.

Similarly, other efforts to fortify cellular-connected UAV networks against DDoS attacks, highlighted in [166], also rely on ML-based techniques. Yet again, the utilization of the CSE- CIC IDS-2018 dataset [167] for attack detection in this context lacks alignment with FANETs and the intricate infrastructure of 5G networks. This makes the dataset less suitable for such UAV-based studies.

A very recent study based on ML [168] focuses on realtime GPS spoofing detection for UAVs. It explores static and dynamic attack scenarios through flights using both authentic GPS signals and simulated spoofing attacks via a software-defined radio (SDR) transceiver module. The study's significant contribution lies in introducing a real-time GPS spoofing detection solution compatible with standard receivers and common modules, eliminating the need for hardware modifications. The study recorded GPS signal attributes during normal and spoofed encounters, and employed various ML algorithms (RF, K-Nearest Neighbors (KNN), SVM, Decision Tree (DT), and Neural Networks (NN)). Notably, the Decision Tree (DT) emerged as the most efficient classifier among these algorithms. The notable effectiveness of the Decision Tree (DT) algorithm in attack detection has been observed in other studies [169] as well. However, the absence of a dedicated FANET dataset in literature prompted the researchers to rely once again on widely recognized datasets like CICIDS-2017 [167].

As stated above, several ML-based studies have previously relied on public datasets gathered from various environments, potentially unsuitable for FANETs. Nonetheless, in the most recent literature, two studies have presented their datasets specifically collected from simulations mimicking FANET environments to address this gap. In [170], an ML-based approach for Sybil attack detection in FANETs is introduced. The study created a FANET dataset by considering the 3D movement and low-density characteristics using the OM-NET++ simulation tool. This dataset encompasses two radio signals: Received Signal Strength Difference (RSS) and Time Difference of Arrival (TDoA), extracted from the physical layer. Reported experimental results showcase a detection rate exceeding 91%, with a claimed false positive rate (FPR) of less than 9%. However, to ensure real-world applicability, further evaluation of the model across diverse attack scenarios becomes essential, as relying solely on a single scenario might not guarantee its overall security.

The other study presented in [171] introduces an attack dataset designed for detecting time delay attacks in FANETs. This dataset gathers latency-related information from preplanned routes established by different routing protocols within simulations conducted via the ONE simulator [172]. Employing ML algorithms, the study detects attacks and utilizes K-means clustering to identify malicious nodes. The study achieves an accuracy exceeding 80% with less than 2.5% overhead across various network configurations. However, its emphasis on pre-planned flight paths, slow speeds (6 m/s), and 2D movements of UAVs limit its suitability to a variety of FANET applications.

Several studies have employed distinct methods such as artificial neural network-based (ANN) and fuzzy-based algorithms to detect specific types of attacks. In [173], an ANNbased approach is proposed for detecting false data injection attacks. It utilized the Thor Flight 111 dataset [174] for model training and evaluated the model's performance based on detection time and false positive rate. However, with increasing network density, a decline in detection rate and an increase in false positive rates were observed. Another study [175] explores the use of neural networks and fuzzy-rule-based IDS for detecting DDoS attacks. The attacks were conducted in real-time against the Parrot AR. Drone. Hence the tests were limited to a single small-scale drone, prompting the need for observation of their effects in a larger network setting. [176] proposed another fuzzy-based IDS for detection various attacks such as wormhole, sinkhole, selective forwarding. Each node computes the trust value of its one-hop neighbors based on its experience and recommendations from neighboring nodes using a fuzzy method.

Deep Learning-based Studies: Various deep learning (DL) approaches have been explored in recent studies for intrusion detection in UAV networks. These methods are proposed in many studies due to their inherent advantages in deciphering complex patterns from data, demonstrating adaptability, and achieving high accuracy in classification tasks. A DL-based approach showcasing the superior performance of Convolutional Neural Networks (CNN) over traditional machine learning algorithms is presented in [177]. The system used encrypted Wi-Fi traffic data records from the UAV-IDS-2020 dataset [178], achieving an accuracy of 99.50% with a prediction time of 2.77 ms.

The implementation of a recurrent neural network (RNN) algorithm is explored in [179]. However, due to the absence of a tailored intrusion dataset for FANETs, training was performed using datasets such as KDDCUP99 [180] and NSL-KDD [181] collected from different network types. The proposed IDS deployed both in each UAV and within GBS. In [182], a Deep Reinforcement Learning (DRL) approach was proposed for training IDS models on the central system. Regular model updates between UAVs and the central station resulted in a higher detection rate but led to significant energy consumption. Hence, an offline learning strategy, wherein model updates occur when UAVs return to the charging station, was suggested to conserve UAV energy while maintaining IDS effectiveness.

In another study [183], DL combined with hierarchical SVM was employed to detect GPS spoofing and jamming attacks in UAVs. Upon detecting an attack, UAVs trigger a Q-learningbased adaptive route learning algorithm to navigate back to a secure zone. However, while the study claimed that DL algorithms provide a lightweight solution for this purpose, no experiments were conducted to validate this assertion.

Federated Learning-based Studies: In [184], a federated learning-based approach detected jamming attacks using two datasets. The first dataset, generated using the ns-3 simulation tool, contained 3,000 samples with eight features like Packet Delivery Ratio, throughput, and Received Signal Strength Indicator. The second dataset adapted the CRAWDAD VANET dataset [185] for FANETs' unbalanced data. Each UAV trained a local model and sent weights to a central system, which aggregated them to form a global model. A selective approach utilizing the dumper-shapher approach reduced communication costs, achieving about 82% accuracy for CRAWDAD and 89.5% for the FANET dataset. Traditional solutions were

shown to yield notably lower accuracy on these datasets. In their extended study [186], a reinforcement federated learningbased method identified a defense strategy in new environments. This approach devises alternative routes avoiding jamming attack areas through spatial retreat.

In [187], an IDS detects GPS jamming and spoofing attacks using an unsupervised federated learning approach with the UAV Attack Dataset [163]. Various federated learning aggregation methods like FedAvg [188], FedAdagrad [189], FedAdam [189], and FedYogi [189], were tested, with FedAvg notably displaying robustness and achieving an F1-score of 0.887.

In a very recent study [190], FL using CNN and DNN algorithms was introduced for detecting FANET routing attacks (blackhole, sinkhole, flooding). A significant contribution was the creation of a comprehensive FANET dataset with 50 nodes featuring 3D movements and essential FANET-specific characteristics. Moreover, they compared IDSs developed via FL, traditional central, and local methods. FL closely approached central IDS performance in most experiments, demonstrating its potential for FANET's distributed architecture. Additionally, they employed the Bias Towards Specific Clients (BTSC) approach to enhance detection performance.

3) Specification-based IDSs: These techniques aim to combine the advantages of both signature-based and anomalybased systems. In such systems, any deviation from system specifications is flagged as a potential attack, enabling the detection of new attacks that do not adhere to these specifications. However, they inherently struggle to detect DoS attacks, as they align closely with the system's specifications. Additionally, defining specifications for all system components is a time-consuming task.

Since routing protocols represent a significant advancement in MANETs, numerous specification-based IDSs focus on detecting routing attacks in this context [40]. To our knowledge, there have not been specific specification-based proposals in FANETs. Adapting MANET proposals to FANETs is plausible, yet detecting more evasive DoS attacks in such dynamic systems should be a key consideration.

4) Hybrid IDSs: A hybrid approach merging signaturebased and statistical-based anomaly detection techniques is proposed in [191] for identifying various types of DDoS attacks targeting FANETs. The signature-based method was tested against two known attack variants and a new type. However, this approach displayed reduced robustness against these new attack types and even variants of existing ones. To address this limitation, a statistical anomaly-based approach was introduced, aiming to enhance detection robustness. In another study [192], a hybrid approach was introduced to detect blackhole, grayhole, GPS spoofing, and jamming attacks in FANETs. Each UAV was equipped with a rule-based local IDS, and an intrusion response system, developed using SVM, was implemented in the GBS. The results highlighted that this hybrid method offered a high level of accuracy and provided a lightweight security solution with minimal overhead.

A trust-based approach was proposed in [193] to detect wormhole and data integrity attacks. In [194], an IDS was described using the *belief* approach to monitor the behavior

 TABLE XII

 OUTLINE OF THE DETECTION STUDIES ON UAVS' SECURITY

Reference	Year	Method	Dataset	Attacks	Simulations
[193]	2016	Trust-based (Belief approach)	No dataset	Wormhole	No sim
[175]	2010	must bused (Bener upprouen)	To dataset	Data integrity	ito biini
[175]	2016	Fuzzy	No dataset	DDoS	Real UAV was used
[192]	2018	Rule-based	a FANET dataset	Blackhole	ns-3
[->=]		ML		Gravhole	2D movement
				GPS spoofing and jamming	50-250 nodes
[98]	2018	Rule-based	No dataset	DoS	ns-3
				False information	100-400 nodes
				injection	
[183]	2019	ML	a FANET dataset	GPS spoofing and jamming	ONE simulator
					2D movement
					20 nodes
[191]	2019	Signature-based	No dataset	CFC	OMNeT++
		Statistical Anomaly-based		PFC	2D movement
[156]	2020	Rule-based	No dataset	Blackhole, Grayhole	Ns-3
				Wormhole and Fake Information Dissemination	100-400 nodes, 2D movement
[169]	2020	ML	CICIDS-2017 [195]	Brute force, DoS	No sim.
				BotNet, Port Scanning	
				SQL Injection, XSS, Heartbleed	•
[184]	2020	FL	CRAWDAD VANET dataset [185]	Jamming	ns-3
			a FANET dataset		3D movement
	2020	FI			4 nodes
[186]	2020	FL	CRAWDAD VANET dataset [185]	Jamming	ns-3
			a FANET dataset		3D movement
[176]	2020	Trust based	No deterat	Dronning	Omnet
[170]	2020	Fuzzy Classification	No dataset	Dropping	2D movement
		Tuzzy Classification			100 nodes
[163]	2020	ML	a UAV dataset	GPS Spoofing	PX4 and Gazebo
[105]	2020	AI	a orre databet	or b bpooning	3D movement
					6 nodes
[179]	2021	DL	KDDCup 99	Backdoor	No sim.
. ,			NSL-KDD	DoS	
			UNSW-NB15	Injection	
			Kyoto	Mitm	
			CICIDS2017 [167]	Password	
			TON_IoT	Scanning	
				XSS	
				Benign	
[166]	2021	ML	CSE-CIC-IDS2018 [167]	DoS, DDoS	No sim.
				Brute Force, BotNet	
[193]	2021	N	CICIDS2017	Brute ferre	No
[182]	2021	DL	CICIDS2017	Des	NO. SIIII.
				D03 Botnet	
				Port scanning	
				SOL injections	
				XSS	
[160]	2021	Rule-based	No dataset	Flooding	OMNeT++
C				e	2D movement
					40 nodes
[173]	2021	AI	Thor Flight 111 dataset [174]	False data injection	No sim.
[161]	2022	ML	DJI Phantom 4 drone datase [162]	DoS attacks	No sim.
[164]	2022	ML	AWID2 dataset [165]	DoS attacks	No sim.
[168]	2023	ML	UAV dataset	GPS Spoofing	a real UAV was used
[170]	2023	ML	a FANET dataset	Sybil	OMNET++
					3D movement
					6 nodes
[171]	2023	ML	FANET dataset	Time Delay	ONE
					2D movement
11073	2022	PI			13,24 nodes
[187]	2023	FL	UAV Attack Dataset [163]	GPS Jamming and Spooting	ino sim.

of each UAV and create a threat level. The IDS was located on each UAVs. The experimentation results showed that, despite a high number of attackers, a low false positive ratio ($\approx 3\%$) and a high detection ratio ($\approx 93\%$) were obtained.

General Discussions: The proposed intrusion detection approaches are summarized in Table XII. While research on UAVs and FANETs is rapidly growing, their security exploration remains in its early developmental stages. Although literature proposes numerous approaches for MANETs and VANETs [196], these solutions might not readily adapt to FANETs due to their higher dynamic topology and distinct mobility patterns and architectures. Nonetheless, the research community might utilize certain solutions from the literature, such as specification-based IDSs developed for specific routing protocols, to develop hybrid solutions.

In our review, we have presented significant studies on intrusion detection in UAVs and FANETs, categorized by intrusion detection methods. Notably, artificial intelligencebased approaches stand out for their ability to uncover complex properties. However, retraining these models within resourceconstrained environments requires careful consideration. Exploring trade-offs between security and resource consumption for different applications with distinct requirements remains an open area for investigation. Additionally, many of these studies rely on datasets not collected from UAVs, raising concerns about their real-world applicability.

Examining IDS architecture and the deployment of proposed solutions is pivotal. Federated learning-based IDS holds promise in ensuring communication privacy among IDS agents. Nevertheless, ensuring the security of these proposed solutions, particularly safeguarding against adversarial attacks on AI-based solutions in highly mobile systems, remains an area requiring further research.

VIII. OPEN ISSUES AND RESEARCH DIRECTIONS

Studies published for preventing and detecting attacks against UAVs and networks of UAVs are listed in Table XI and Table XII. As can be seen, the research on FANETs and UAV communication is still at an early stage, hence there are currently only limited studies on the securing of such networks. UAVs are used in many applications including those that are considered mission-critical, which naturally make them prime targets for attacks. While a good number of security solutions have been proposed for MANETs and VANETs, FANETs have different requirements to other ad hoc networks. Very high node mobility in 3D, dynamic topology, low density networks, and nodes with small batteries are some of the biggest differences resulting in challenges faced by FANETs from the security perspective. Hence, there is a need to explore novel prevention and detection techniques tailored specifically for FANETs. These methods should account for the network's unique features, whether by devising new solutions or adapting existing security approaches.

The studies on the security of UAVs and FANETs have accelerated in the very few years, reflecting the growing recognition of the vulnerabilities inherent in these systems. However, a critical analysis reveals several gaps and challenges that warrant further investigation. In the subsequent sections, we delve into a detailed examination of the identified shortcomings in the existing literature, shedding light on specific areas where research efforts could be directed to fortify the security state of UAVs and FANETs.

Limitations in Simulation Environments:

The published studies have generally been either not evaluated or tested within simulation environments as shown in Table XII. However, these simulations should reflect real-world flight dynamics and 3D movements of UAVs. Unfortunately, however, this has not been the case in the literature. To the best of the authors knowledge, approaches for securing FANETs have been generally simulated on networks where nodes move only in 2D, and only a few studies [36], [170], [186] have implemented the 3D movement of UAVs in their simulations. Furthermore, some studies have utilized parameters such as a small number of nodes [171], [183] or low speeds that are more suited to MANETs [192], [197], [198]. Therefore, we believe that the analysis of attacks carried out in more realistic real-world scenarios, as exampled in the current study, is an important initial study which aims to accelerate the research in this important area.

While proposing and assessing security solutions for UAV communication, it is pivotal to assess their adaptability across diverse tasks and applications. Factors like the presence of central nodes and the mobility patterns of these nodes can significantly influence the performance of proposed security solutions. For instance, certain missions may require coordinated movement of UAVs in a specific direction, followed by periodic reorientation towards the controller ground system. As a result, security solutions are only practical and effective if they are aligned with these mission-specific network configurations. The absence of mission-specific simulations in current literature is a notable gap. This limits our ability to assess security proposals within real-world mission contexts. Incorporating realistic network settings aligned with specific missions is an unexplored area that hampers the development of tailored security solutions optimized for diverse UAV operations.

GBS- Overlooked Asset in UAV Security:

Unlike typical ad hoc networks, which lack central points and distribute data across nodes, GBS play a vital role in various UAV applications. GBS serve essential functions such as data aggregation, decision-making, and more. Security proposals in these scenarios can leverage the presence of central nodes within UAV operations. Given their superior computational powers and ample resources compared to UAVs, these central stations can execute more robust algorithms, thereby enhancing the security measures implemented within the network. Additionally, the deployment of these nodes, whether in static or mobile capacities, opens avenues for innovative security solutions. As static central nodes, much like returning to the trusted comfort of a mother's embrace, GBS provide a reliable hub for tasks like updating models or databases, integrating signatures, and establishing rules during UAV battery charging at these stations [182]. Similarly, in their mobile capacity, they can undertake similar tasks. Exploring various alternatives becomes crucial, considering network density, mobility characteristics, and diverse applications.

In addition, the vulnerability of GBS remains insufficiently analyzed, despite their critical role in UAV operations. Existing studies predominantly concentrate on attacks against UAVs, overlooking potential threats to GBS. Attacks targeting these central nodes could have significant consequence, given their status as potential single point-of-failure in certain tasks. Moreover, the impact of such attacks can vary based on whether these central nodes are static or dynamic, underscoring the need for comprehensive assessment and mitigation strategies.

Need for Increased Attention to Architectural Aspects:

While studies predominantly concentrate on their methods, they often neglect to address the architectural aspects in their proposals. For instance, in certain applications, UAVs might operate collectively, moving together in a specific direction to accomplish tasks. In such densely coordinated systems, a distributed and cooperative architecture is likely to yield superior performance compared to a network where UAVs move randomly and autonomously, resulting in sporadic connectivity. Moreover, as pointed out above, the positive inclusion of GBS in a hybrid or hierarchical architecture should be further explored.

In a distributed and cooperative architecture, prioritizing privacy and secure communication among agents is critical. Blockchain technology has shown promise in addressing these concerns, as evidenced by several studies exploring its applications in this research domain [47] [49]. However, the use and deployment of blockchain in UAVs with energy, computation, data storage resource constraints needs further examination. Another impactful approach is the utilization of federated learning, particularly in bolstering the performance of machine learning methods for security purposes. Federated learning involves transferring local models' parameters, instead of large data volumes, to train a global model and redistribute its parameters to local models. This approach holds significant potential for highly dynamic networks prone to frequent link disruptions, where a distributed and cooperative solution is likely to outperform traditional methods. Notably, federated learning addresses privacy concerns inherent in such systems.

Existing literature showcases federated learning-based approaches for intrusion detection. Studies, such as those aimed at detecting jamming attacks [184] [186], and recent research [190] comparing FL-based proposals with central and local architectures, demonstrate the potential of federated learning in terms of accuracy, security, and communication cost. Future research should explore federated learning-based systems for various attack types. Further investigation is warranted in the realm of blockchain-based federated learning [136]. Greater emphasis is needed to understand and mitigate attacks against federated learning systems, such as fake parameter updates or model poisoning attacks in general, backdoor attacks. In addition, convergence challenges due to device heterogeneity, and communication delays during parameter collection and redistribution among local nodes should be taken into account [136].

Connectivity among nodes is another critical architectural consideration in UAV networks. The high speeds of UAVs can lead to intermittent connectivity, causing potential communication disruptions. Moreover, relying on wireless links heightens susceptibility to packet drops, impacting network reliability. These challenges complicate real-time data monitoring and must be carefully addressed in architectural design to ensure robust communication for security solutions. An alternative solution could be an Internet of Digital Twin UAVs in the cloud, capable of gathering traffic information from other twin UAVs [199]. The integration of Digital Twin technology for enhancing the security of UAVs represents an emerging area of research that warrants further exploration.

ML-based Approaches:

UAVs high mobility and energy constraints make them very challenging for manual proposals. Hence, artificial intelligence-based studies offer promising solutions with their ability to automatically discover the complex characteristics of a system. Therefore, researches investigate the use of machine learning techniques for UAV's security. While a few security proposals have been based on machine learning [166], [169], [183] and deep learning [179], [182] for UAVs and FANETs, most of these studies have utilized public datasets proposed for environments other than FANETs. Moreover, even in the simulations applied in [171], [183], the nodes used moved only in 2D. Thus, there is a clear need for additional research to thoroughly evaluate the practical implementation of these methods in real-world scenarios.

A multi-level security system that incorporates anomaly detection across various aspects can be quite robust. For instance, anomalies detected in sensor inputs, routing packets, and communication between UAVs and the Ground Base Station (GBS) could collectively indicate a potential intrusion. This layered approach enhances the overall security posture by monitoring multiple levels for potential threats, hence an open research area.

In addition, the security of ML-based solutions should be taken into account. Adversarial attacks, especially in mobile environments, require further investigation. The dynamic and lossy nature of UAV networks makes distinguishing between normal and abnormal behavior challenging, leaving room for exploitation by attackers. As pointed above, secure communication among agents running ML algorithms locally can be achieved through blockchain or federated learning. Blockchain-assisted federated learning [200] facilitates decentralized model aggregation, eliminating the vulnerability of a central aggregator. Moreover, involving only authorized UAVs' local models in updating the system's model [201] could mitigate poisoning attacks. Designing lightweight blockchains for UAVs presents a promising area of investigation due to its inherent advantages [202].

Resource Constraints:

Resource consumption is another constraint and critical issue that needs to be addressed when designing security solutions for UAVs and FANETs. As some missions necessitate the deployment of small-sized UAVs having constraints in processing power, memory, and energy, such nodes may be more susceptible to attacks. It is essential to develop secure protocols or security solutions tailored for UAVs and FANETs that operate within stringent resource constraints. This involves developing protocols that ensure both security and efficiency, implementing appropriate access control and key management mechanisms, optimizing cryptographic techniques, authentication methods, and IDSs to operate effectively while minimizing resource usage within UAVs' limited capabilities.

In order to protect small-sized UAVs, lightweight solutions should be designed, and certain proposals in the literature have already targeted this aim [182], [183], [192]. These proposals have generally claimed their approaches to be lightweight due to the use of a known lightweight approach such as deep learning [183], or where it is considered to generate only a low overhead [192]. However, differences in the trade-offs between effectiveness and resource consumption have not been discussed in these proposals. Different trade-offs may be more suited to certain tasks or missions, hence this consideration requires considerable exploration.

In addition, the effectiveness of lightweight solutions with the inclusion of other nodes and a ground central system could be improved, and is also worthy of further investigation. GBS typically possess superior computation capabilities and energy resources compared to small-sized UAVs, which are constrained by limited battery power. Additionally, GBS could be deployable in either static or mobile configurations based on specific application needs. These central nodes can be utilized for tasks such as updating models or databases, incorporating signatures and rules during UAV battery charging at these stations [182].

Strengthening Security with Emerging Technologies:

In real-world scenarios, UAVs have the capability to interact with IoT devices, MANETs, VANETs or other systems. This capability not only enables UAVs to increase connectivity by working as a relay node in such systems but also bases the groundwork for UAV-assisted security solutions. These solutions play a crucial role in averting potential security vulnerabilities that may arise when diverse devices are integrated within hybrid environments. For instance, in [203], how UAVs can aid in reducing security risks in IoT systems against eavesdropping attacks is explored. A UAV acting as a relay receives packages to provide transmission to a specific destination and aims for their successful delivery. Another approach [204] uses UAVs as friendly jammers in order to deter unidentified eavesdroppers using artificial noise. When an eavesdropper is detected, they serve as relays between vehicles to prevent information leaks.

We expect to see more applications of UAV-assisted networks or IoT, since such systems make it possible to access locations where humans cannot access in applications such as emergency search and rescue and military. Exploring security solutions for such hybrid systems that cover all components with diverse characteristics is a new area of investigation. Additionally, the utilization of UAVs to enhance security in IoT or other network types is worth further exploration. Emerging areas such as UAV-assisted blockchain [205], trust [206], and intrusion detection [203] are all areas that deserve deeper examination.

UAVs could also assist in Mobile Edge Computing (MEC), which involves offloading tasks to mobile edges to meet the requirements such as decreased latency, real-time processing, and enhanced Quality of Experience of next-wave applications like augmented reality and ultra-high definition video streaming [207]. Security presents a significant challenge in these systems, particularly for real-time applications where security and latency are competing factors. Future research directions for securing UAV-assisted MEC highlight areas such as PLS, machine learning, blockchain, and authentication protocols [207].

Enhancing the security of UAVs using emerging technologies such as digital twins or the Internet of Digital Twins represents a highly promising area for research. Beyond security improvements, digital twins offer capabilities for anomaly detection, early failure detection, and more. These systems can complement traditional security solutions, particularly when certain UAV agents face connectivity issues or device failures. Exploring methods to model UAVs and their communication within digital twin frameworks, as well as identifying meaningful semantic data for security purposes, are key areas that demand further study.

Other Aspects- Diversity of Applications and Standards:

UAVs can be used in various applications with various security requirements, ranging from military applications to civilian tasks such as infrastructure inspection, agricultural monitoring, environmental surveys, disaster management, and aerial photography, among others. Hence, when designing security solutions, the specific needs and diverse communication patterns inherent in different applications should be taken into account. As pointed in above, such mission-specific or scenario-based simulations is a notable gap in the literature. This gap also underscores the critical necessity for advancements in protocols and standards. Notably, existing standards provide varying levels of support for UAV communication, traffic management and flight operation among UAVs [208]-[210]. Many standards such as UASSC [210], PODIUM [209] focus solely on communication among homogeneous UAV, while others, like JAUS [208], extend their scope to accommodate heterogeneous UAV systems. Enhancing these protocols and standards is a pivotal step in addressing the growing challenges faced by UAV system security.

To summarize, UAVs bring about new challenges from the security perspective. Whilst there have already been studies published in this area, the research is still at an early stage. The development of suitable solutions are still needed for such dynamic and resource-constrained systems, and the deployment and evaluation of these solutions is an important area in which further exploration is necessary.

IX. CONCLUSION

The increasing numbers and expanding applications of UAVs in both military and civilian domains have made them vulnerable targets for various attacks. This review study aims to comprehensively explore the security issues concerning UAVs and their communications facilitated by FANETs in various operational tasks. While existing research has extensively covered MANETs and VANETs in the literature, it is crucial to analyze FANETs due to their distinct characteristics, strengths, and vulnerabilities.

Initially, we evaluate the specific characteristics of UAVs and FANETs, considering their unique requirements and discussing their implications for security. Then, we present the attack surface analysis, which is one of the important contributions of this study. This analysis not only illuminates vulnerabilities within UAVs and FANETs but also serves as a foundation for identifying novel threats. The survey strategically aligns a taxonomy of attacks targeting UAVs and FANETs based on the attack surface analysis.

This study transcends a standard review by integrating an attack analysis based on extensive simulations. Four attacks against FANETs, including blackhole, sinkhole, drooping, and flooding attacks, are simulated using realistic real-world scenarios to illustrate the varying implications and potential results of each attack within the network. Then, the proposed solutions based on prevention and detection are presented and discussed. Finally, we have thoroughly explored open issues and research directions, ensuring a comprehensive understanding of the latest developments and their interdependence with related areas.

We believe this study offers a comprehensive survey covering security issues in UAVs and FANETs. It presents a taxonomy of attacks based on the attack surface analysis, conducts simulations and analysis of attacks in real-world scenarios, and discusses proposed security solutions in the literature, along with detailed research directions. The utilization of attack surface analysis allows for a more comprehensive understanding of the security landscape of UAVs. By thoroughly exploring open issues and delineating promising research directions, our study aims to pave new pathways within this research domain. Considering the accelerating focus on UAV security in recent years, we believe this study is timely and beneficial for researchers.

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