

An Autonomous Smart Metering Infrastructure Based on UAV Swarm: Planning and Design

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Abstract: This research paper proposes a novel autonomous smart metering infrastructure based on a swarm of Unmanned Aerial Vehicles (UAVs), or drones. This infrastructure aims to overcome the limitations of traditional smart city applications by leveraging the flexibility, mobility, and scalability of UAV swarms. The proposed system comprises a Data Management Center (DMC) responsible for mission control and data analysis, and a self-organizing network of UAVs capable of autonomously executing pre-defined tasks. The paper details the system's operational framework, including initialization, flight, and data collection phases. Crucially, it addresses potential failure points and introduces novel failure prediction and recovery procedures to ensure system reliability. The paper also proposes specific system messages and communication protocols to facilitate efficient data exchange and coordination within the swarm. Finally, a mathematical evaluation of the system is presented, providing insights into expected latency and throughput for various scenarios. This research contributes to the growing body of knowledge on UAV applications in smart cities, paving the way for safer, more efficient, and resilient urban environments.

Keywords: Smart City, UAV Swarm, Smart Metering, Self-Organizing Network, Failure Recovery.

1. Introduction

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have become ubiquitous tools across diverse fields, proving their efficacy in applications ranging from military operations [1] and agriculture [2] to search and rescue missions [3], environmental monitoring [4], delivery services [5], and healthcare services [6]. However, employing single UAVs presents limitations in coverage, reliability, and scalability.

This is where the concept of UAV swarms emerges, offering significant advantages over single UAV operations, particularly in efficiency, resilience, scalability, cost-effectiveness as well as real-time responsiveness [7-9]. Inspired by the collective behaviors observed in nature, such as bird flocks, fish schools, and insect swarms [10], UAV swarm research focuses on developing technology that enables these aerial collectives to navigate autonomously, adapt to dynamic environments, and accomplish complex missions with enhanced efficiency and resilience compared to single UAVs [11 - 12]. Formation flying, a specific type of swarm operation, offers substantial benefits for tasks demanding coordinated effort, efficiency, and precision. UAV formation control, therefore, aims to manage and guide multiple UAVs flying in a precise geometric arrangement or pattern, ensuring each UAV maintains its relative position, speed, and orientation within the group, adapting to changes in external conditions and internal factors like UAV failures [13].

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The problem of formation control has been extensively studied within the context of UAV swarms and multi-agent systems (MAS), where UAVs are treated as individual agents. Do et al. [13] provide a comprehensive survey of formation control algorithms for UAVs, examining various approaches including leader-follower, virtual structure, behavior-based, artificial potential field (APF), and consensus-based methods, as well as intelligent methods. Ouyang et al. [14] further compared existing formation control strategies, emphasizing the future trends of decentralization and intelligence in UAV swarm control.

Oh et al. [15] categorized formation control methods based on sensing capabilities and interaction topology, distinguishing between position-, displacement-, and distance-based control. Similarly, Liu et al. [16] discussed distributed formation control methods based on position and displacement in global coordinates, as well as distance and bearing in non-global coordinates. Chen et al. [17] classified existing methods into communication-based and vision-based control, highlighting the diversity in information flow between agents.

Despite these advancements, UAV swarm formation control still faces significant challenges, particularly in scalability, robustness, and environmental adaptability [18]. The recent surge in Artificial Intelligence (AI) algorithms, such as Artificial Neural Networks (ANNs) [19] and Deep Reinforcement Learning (DRL) [20], offers promising solutions. These data-driven paradigms offer a more general approach to formation control, potentially overcoming limitations of conventional model-based methods. Applying AI to UAV swarm formation control promises advantages like autonomous decision-making, efficient coordination, and robustness to failures, further enhancing effectiveness, flexibility, and scalability. However, implementing AI introduces its own set of challenges, including computational complexity and the need for extensive training data.

When revising the literature, as mentioned earlier, there was not much effort went into applying drone swarm solutions to enhance smart city performance, reduce the risk to human lives, and promote its citizens' welfare. Yet, a full descriptive framework that provides information about the swarm nodes and used hardware, their architecture, exchanged messages, and adopted networking and

communication protocols, that meet certain reliability and security requirements, has not been established. In this paper, the idea of adopting UAVs in a swarm as part of the smart metering infrastructure will be planned, designed, and discussed in detail, leading to a complete framework description involving system phases, e.g. initialization and operation, as well as exceptions, i.e. failure management.

The remaining paper is organized as follows. Section 2 presents the outlines of smart metering infrastructure, Section 3 about proposed system mathematical evaluation, and Section 4 presents the conclusions

2. The Proposed Smart Metering Infrastructure (SMI) Outlines

Smart Metering Infrastructure (SMI) refers to the integrated system of advanced metering technologies, data management systems, and communication networks used to monitor, collect, and analyze utility usage data in real-time. This infrastructure is primarily used in utility services such as electricity, water, and gas to provide detailed and accurate consumption information to both utility providers and consumers.

The integration of drones and Unmanned Aerial Vehicles (UAVs) into smart metering infrastructure (SMI) represents a significant advancement over traditional methods. This innovative approach leverages the autonomous capabilities of UAVs to enhance efficiency, scalability, and reliability in monitoring and managing urban utilities.

Traditional smart metering systems involve extensive human intervention for data collection, maintenance, and troubleshooting. This process can be time-consuming, prone to errors, and often requires significant manpower, especially in hard-to-reach or hazardous areas. The idea behind using drones and UAVs in SMI is to create an autonomous, efficient, and scalable solution that minimizes human involvement while maximizing data accuracy and system reliability.

UAV-Level Components are:

- **Leader Drones (LDs):** Coordinate the UAV swarm, manage data collection, and communicate with ground control.
- **Slave Drones (SDs):** Perform individual meter readings and collect data from smart meters.

Ground-Level Components are:

- **Data Management Center (DMC):** Central hub for data processing, storage, and analysis.
- **Communication Infrastructure:** Ensures reliable data transmission between UAVs and the DMC.

The idea to be considered is allowing a robot swarm, i.e. UAVs, to conduct and complete a pre-defined mission autonomously in a reliable and secure way. Thereby, minimal human intervention is needed to carry out a certain task which significantly reduces risking human lives. The suggested system is general and could be applied to different smart city applications, however, a normal procedure needs to be followed when launching missions in such applications. The common elements for such smart infrastructure are mainly the UAV swarm itself and the Data Management Center (DMC), where the drones are kept, configured, and maintained, as well as the mission data collected, processed, and analyzed. According to this, three phases could be noticed throughout the mission lifetime as shown in Fig. 1, which are:

- **The Data Management Center (DMC) Phase:** In this phase, drones are either being configured

and aggregated in a swarm to carry out a pre-planned task or have already arrived after accomplishing a certain mission. In either scenario, the drone’s operator is responsible for preparing, maintaining, and exchanging mission information between the UAVs and the DMC server.

- **The Flying Phase:** To carry out a specific task, drones need to fly from the DMC toward the area of interest, and then fly back to the DMC, or drone homing. This could involve multiple swarm formation and deployment procedures depending on the application itself.
- **The Data Collection Phase:** This phase is when required data is sensed and gathered. UAVs are equipped with the required sensors as payload and can collect data during flight or while stationary, i.e. hovering or landing based on application, also other parameters could differ such as task duration, frequency of readings and reports, real-time traffic, swarm formation, and inter-UAV distance, to mention a few.

Each phase has its own design requirements. For instance, the DMC phase is where the operator prepares the UAVs for a mission, thus, a mission information file should be uploaded so UAVs know where to go at what speed, altitude, and formation.

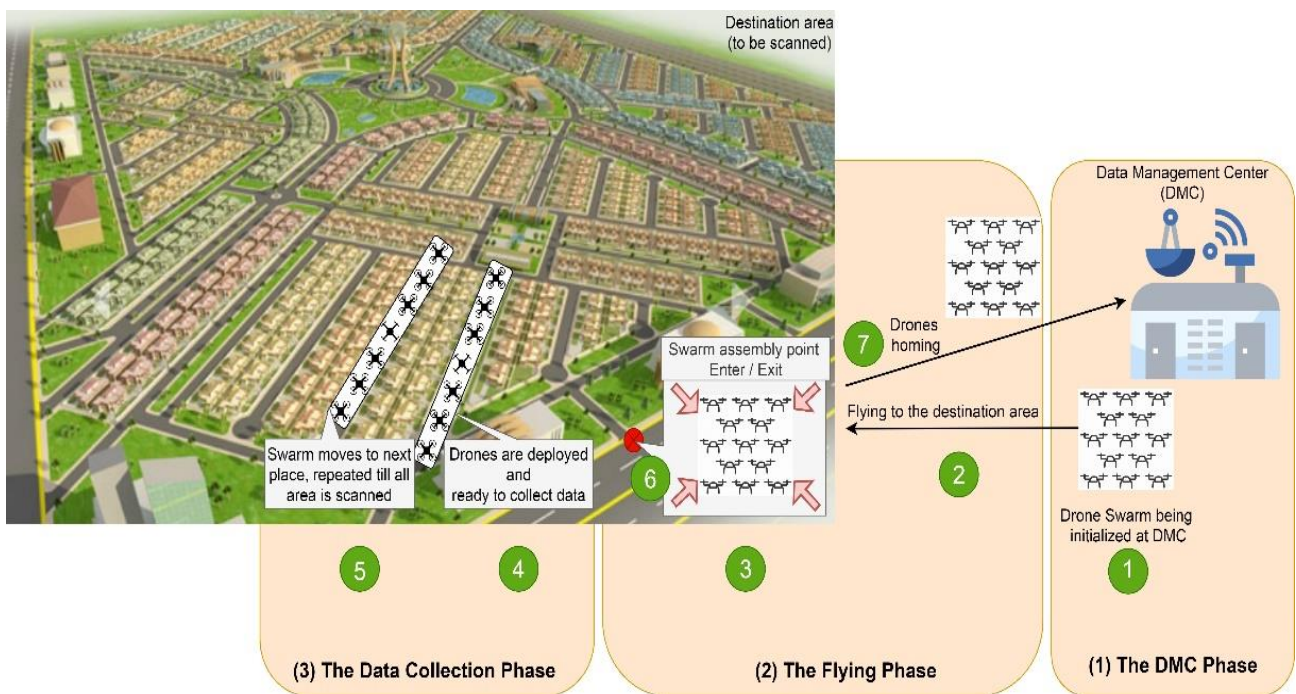


Fig. 1: The proposed system procedural diagram.

During the flight, drones should be synchronized and fly steadily in a certain formation so as not to collide with each other, hence, applying a certain procedure of orchestration is critical. Finally, during data collection, UAVs should know what to do and when, and again coordination is required to achieve mission objectives. The role of a Self-Organizing Network (SON) is vital in such systems not only for performing efficiently, utilizing self-configuration and self-optimization features but also for handling failures when they occur by using the self-healing feature of SONs.

2.1 The Proposed System Framework

The framework description for the suggested approach should consider all contributing elements and possible stages that the system generally and the UAV swarm platform specifically could go through. Therefore, the state diagram method is used to illustrate the possible states and transitions when describing the system. The general scheme for the system is shown in Fig. 2, where the states present possible swarm status

during the mission, and the arrows indicate the events and procedures to transit from one state to another.

The idle state is when the UAVs are inactive, this state could last for a long time until they are assigned to a new mission. As a result, the initialization procedure will take place where the operator will determine the size of the swarm according to the objective task, and assign the Leader Drone (LD), which is responsible for coordinating the swarm and represents the gateway to the DMC while in mission, with all required task information by uploading a certain file called mission information file, which contains target Global Positioning System (GPS) locations, formation type, speed, altitude, type data to be measured, etc. and other task-associated Slave Drones (SDs) will connect to the LD to form a swarm, this will lead to moving to the next state, which is the initialized state. Now the swarm is ready to be launched and start the mission, so when the LD receives a launch command, it will start taking off and commanding other SDs to hover in a certain formation, and when all SDs positively acknowledge their status, the swarm members will start moving towards the target area.

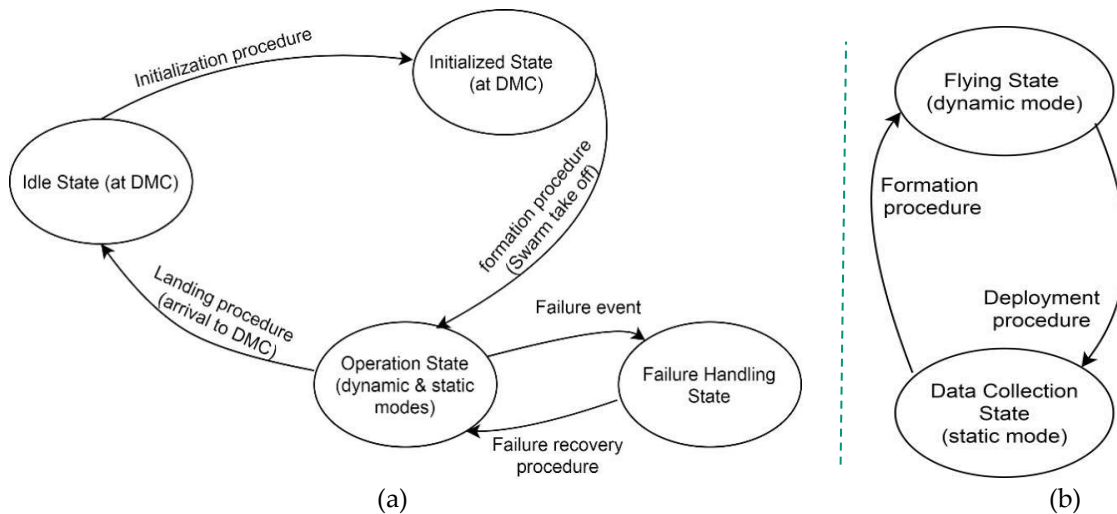


Fig. 2: Main system state diagrams: (a) System overview (b) Operational modes.

The swarm now is in the operational state that could be either mobile (flying) or stationary (hovering or landed), mobility is referred to as dynamic mode, and stationary as static mode although collecting information could be at any time during the operational mode, in the proposed approach, and for the sake of simplicity, data collection is considered when UAVs are stationary, and hence, gathering data is associated with

the static mode. During operation, there could be multiple formations and deployments of the UAVs, and these states are shown in Fig. 2(b). Finally, a UAV could fail for many reasons, e.g. collision or hardware failure, so the swarm will be in the failure handling state to overcome this issue and compensate for the loss if possible.

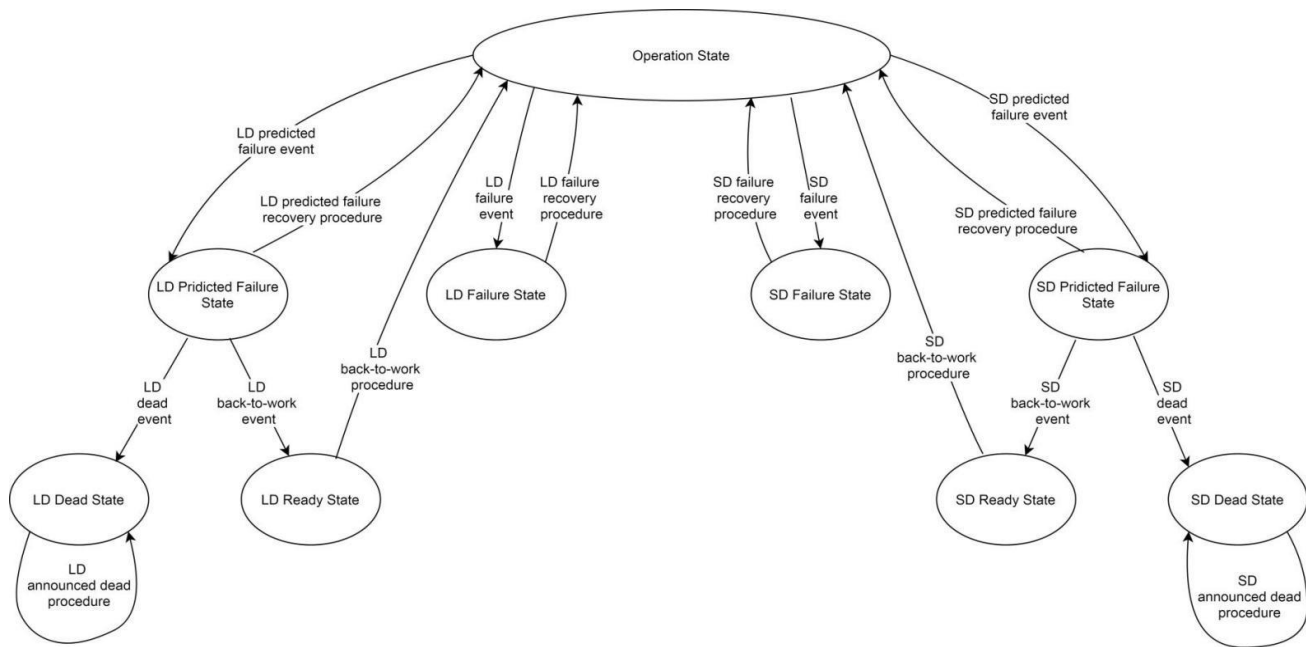


Fig. 3: Failure handling diagram

Fig. 3 shows the failure handling states in more detail. Any swarm node is prone to failure and should be considered when designing such a system. As the LD is in charge of swarm coordination and connection to the DMC, its loss will impact the whole mission greatly. There will be no progress in the mission as the SDs are neither able to communicate with the DMC nor coordinate again, so such vital loss should be well considered and tackled. Therefore, a backup drone that has the most necessary LD capabilities is to be one of the SDs and will take the lead as a backup LD if the original LD is no longer available (hard handover). To further enhance the reliability of the system, if the LD expects a coming failure, e.g. hardware overheating or low battery, then it alarms the swarm with its state and the backup drone will take the lead (soft handover) and all other SDs will disconnect from the original LD and reconnect to the backup LD, meanwhile, the LD will go into the power-saving mode in an attempt to rest and alleviate the anticipated problem and is being enquired for a current status report by the backup LD. If the LD is ready to take the lead back again, then SDs will reconnect to it. However, if the LD is not available anymore, e.g. flat battery, then it is announced as a dead node. The same scenario could happen to any SD, where the LD will assign another SD to carry out the suspended tasks and enquire about the status reports of the predicted failure SD if any, and if the SD is back then it will be assigned tasks again, otherwise, if it is not

responding for a certain time then a node dead announcement is declared.

2.1.1 The Initialization Procedure

Both DMC and UAVs are involved in this procedure, where the drone operator switches on the required UAVs, starting with the LD to be connected to a dedicated server, and a mission information file that includes the needed information to conduct the mission such as GPS waypoints, swarm size, nodes IDs, formation type, speed, altitude, frequency of sending reports, etc. then other SDs will be connected to the LD, and the LD will send a copy of the mission information file to the backup drone, which also has a cellular capability and can communicate to the DMC while in operation. Each received message or data will be acknowledged to confirm its reception. Fig. 4 explains in detail the initialization steps for each system node.

2.1.2 The Formation Procedure

After the initialization of the UAV swarm, it is ready to carry out the required mission by flying to the destination area, sensing, and collecting data. The first stage of operating a mission is for the swarm to fly in formation. Therefore, the formation should be achieved first so no collision will occur.

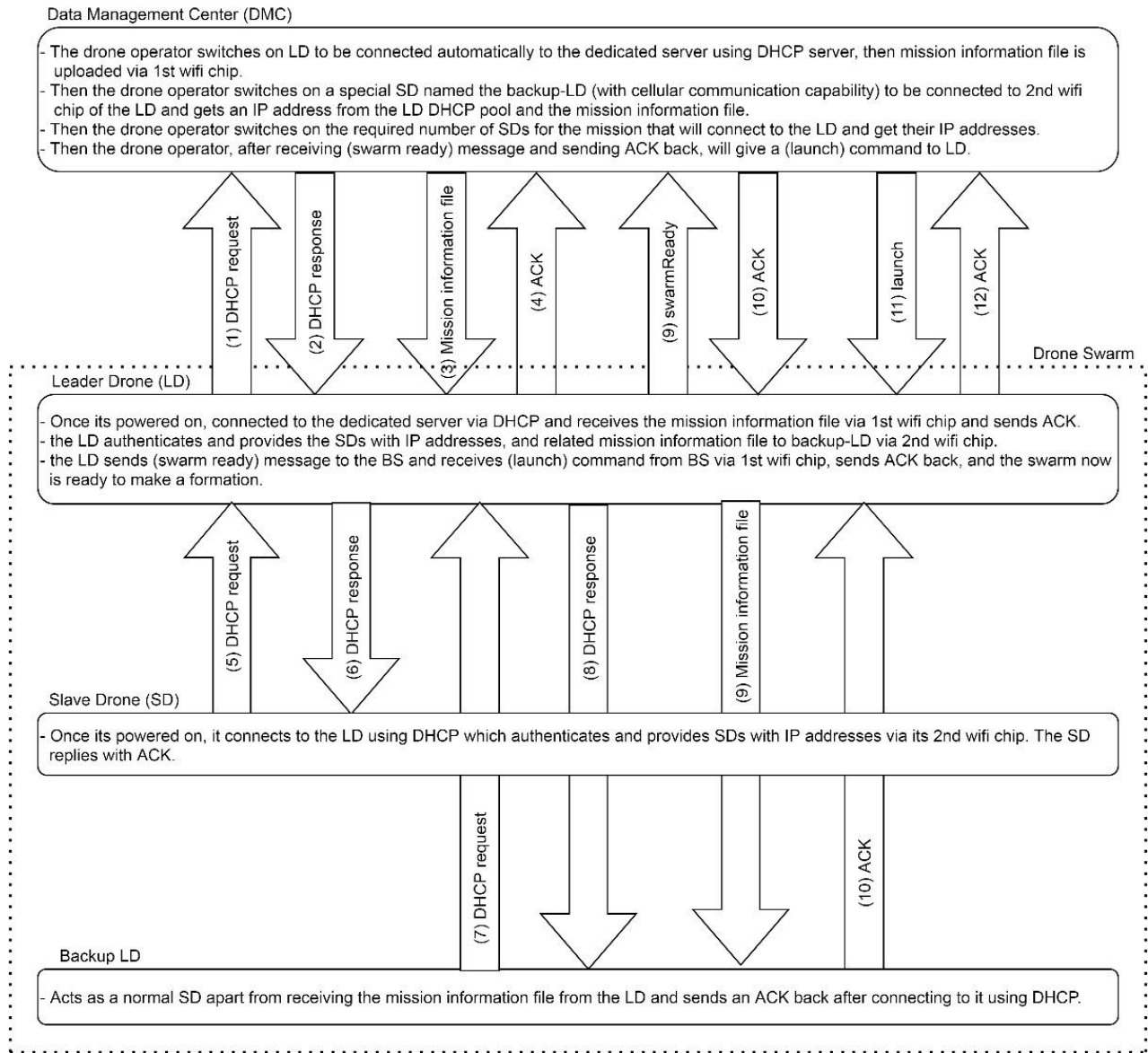


Fig. 4: The initialization procedure.

The LD, as a coordinator of the swarm, will fly to the center of the formation and broadcast its new GPS coordinates to the SDs, which in turn, calculate their relative position in the formation taking the LD as a reference. See Fig. 5, the swarm hovers in the air in the given formation at the end of this procedure.

2.1.3 The Operational Procedure (Dynamic Mode)

Dynamic mode means the swarm is mobile during flight. It is important to keep a high level of synchronization during flight so that neither a UAV goes out of the swarm nor collides with another UAV. Therefore, the swarm should be well orchestrated by

the LD, see **Error! Reference source not found.**, and the SDs should receive coordination messages, process them, and move accordingly in a real-time manner.

The LD should frequently broadcast the coordination command (move To Way point) to all SDs in every (t_{wp}) and sends the swarm aggregated status report periodically to the DMC every (t_{LD}). Similarly, the SDs follow the coordination command and move to their relative position as well as send their status report to the LD every (t_{SD}). All exchanged messages are replied to with an acknowledgment to indicate their reception.

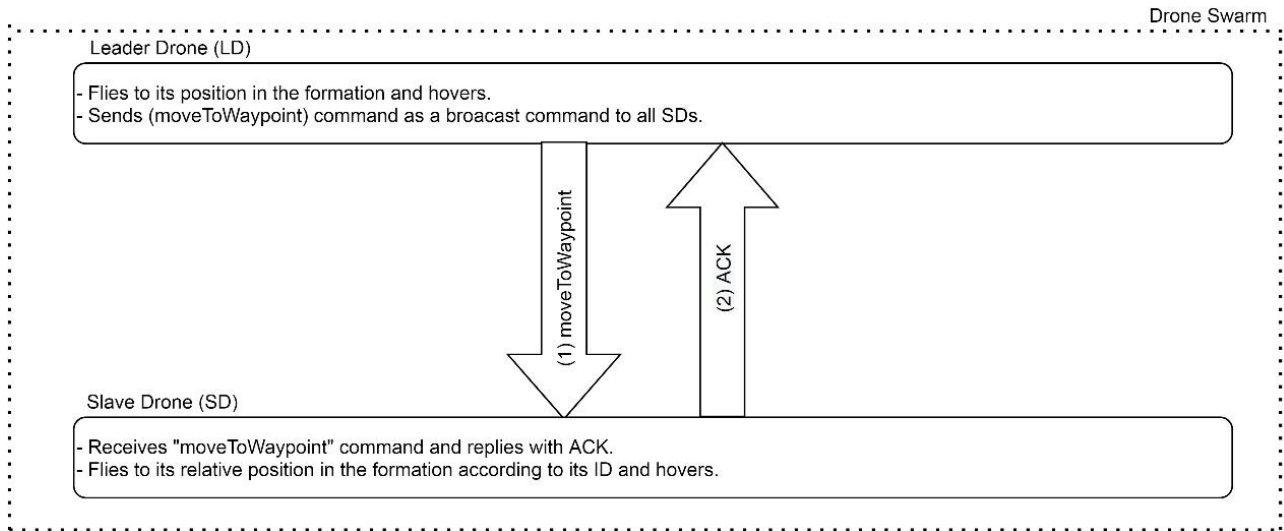


Fig. 5: The formation procedure.

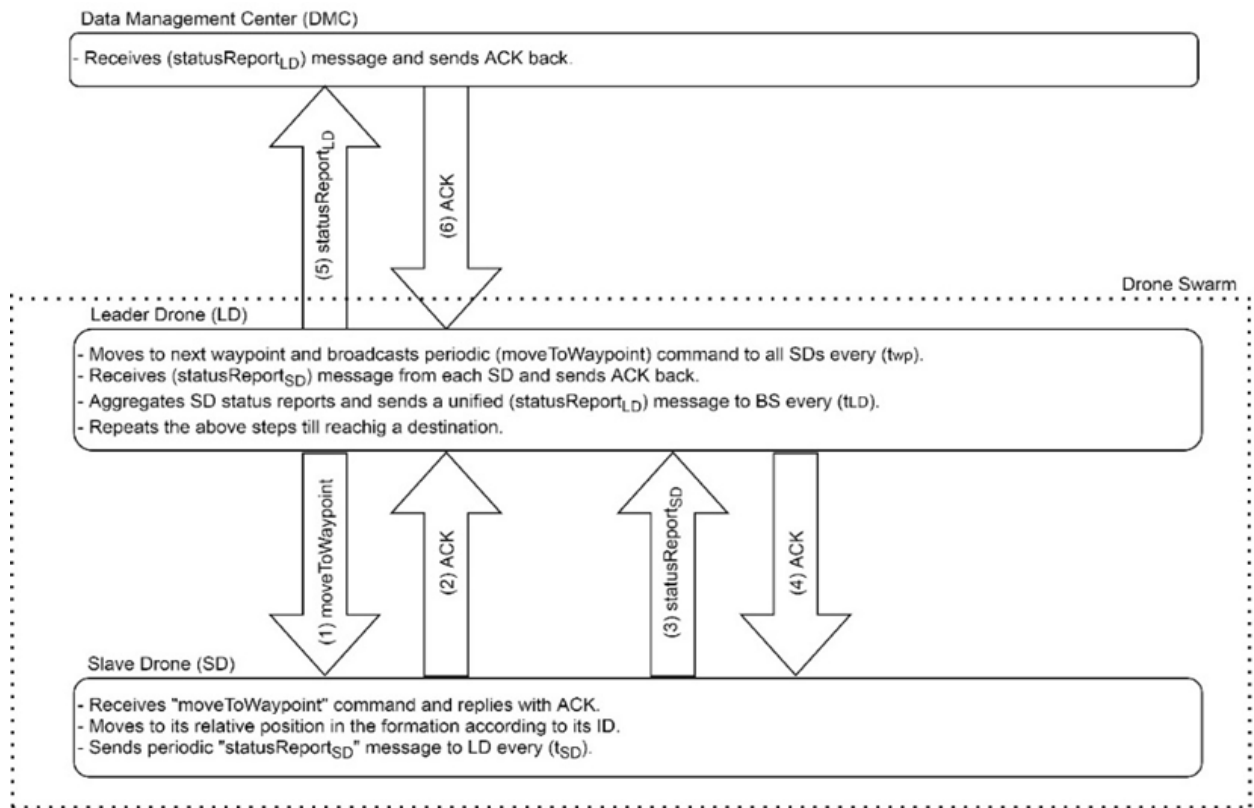


Fig. 6: The operational procedure in dynamic mode.

2.1.4 The Deployment Procedure

When arriving at the target waypoint, a UAV swarm may need to be deployed for data gathering at the destination area, or simply landing at DMC after completing a mission and drone homing, as shown in Fig. 7.

2.1.5 The Operational Procedure (Static Mode)

This is when data is collected in the proposed system. After landing and successful deployment, UAVs turn off their propellers and enter the power-saving mode to save energy.

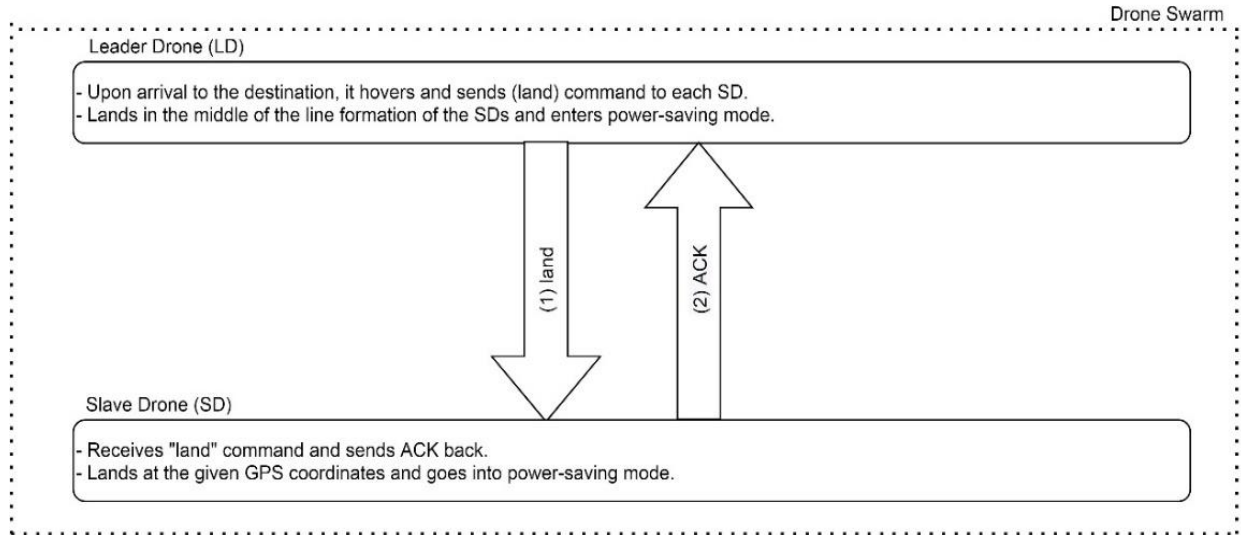


Fig. 7: The deployment procedure.

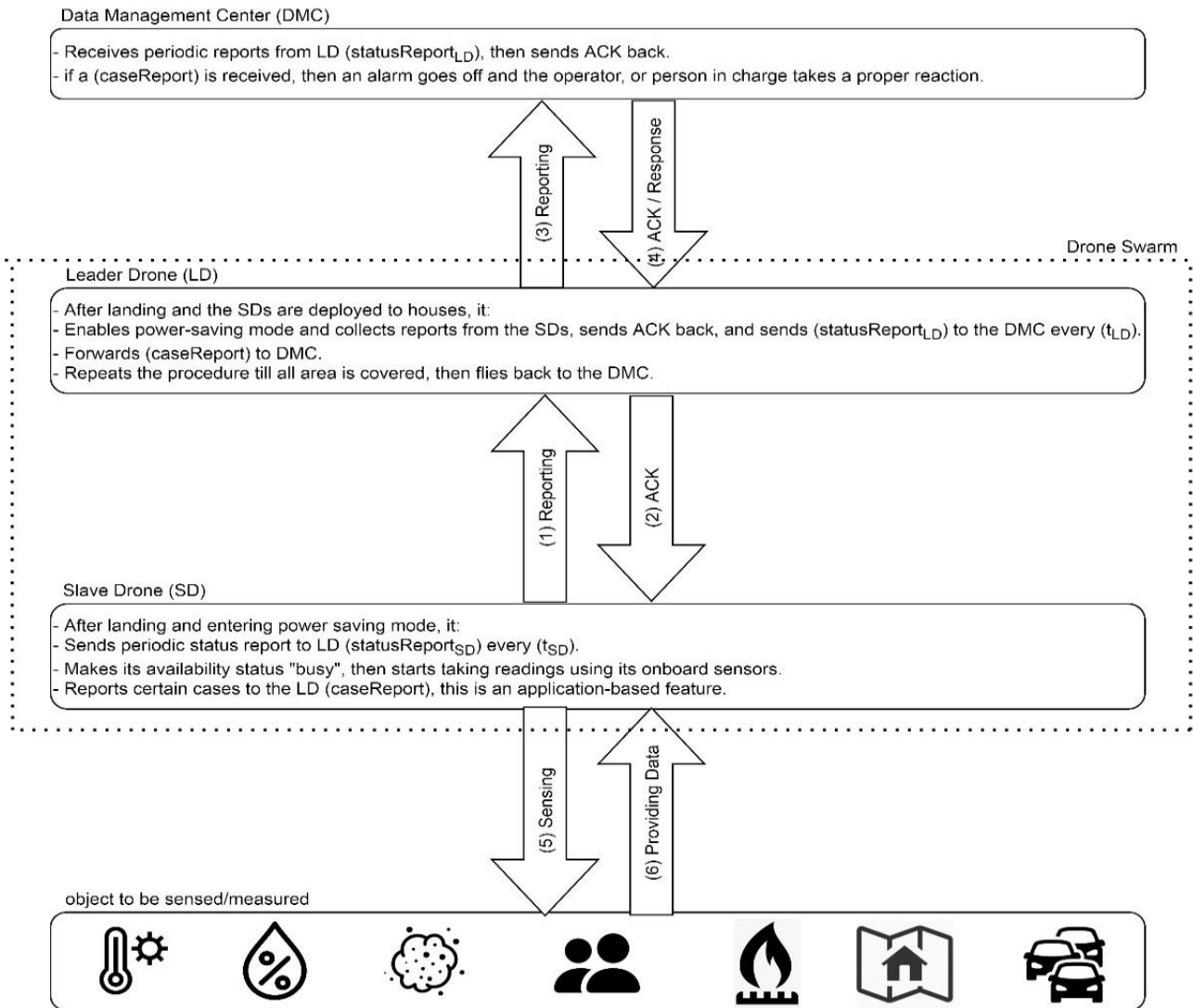


Fig. 8: The operational procedure in static mode.

Meanwhile, SDs gather required data according to the application type and send reports of their current status to the LD which, in turn, aggregates the information of SD status reports and generates a single swarm report for the DMC as when operating in the dynamic mode. This procedure differs from one application to another, some applications need to trigger an alarm if a certain event has been sensed, and others require real-time monitoring of the measured data. Therefore, the proposed approach is designed to be as general as possible so a wide spectrum of applications can be covered, as shown in Fig. 8. Only SDs are considered the sensing units as they are equipped with the required sensors, while the LD is designed to coordinate the swarm and act as the gateway to the DMC. SDs have the onboard processing capability to support future scalability.

2.1.6 The LD Failure Recovery Procedure

A drone may fail for many reasons like collision, flat battery, hardware malfunction, or even a security attack, e.g. hijack. The LD is the swarm orchestrator which without the swarm cannot make any mission progress. Therefore, mitigating such an issue of losing the LD is a must to provide some degree of reliability to the proposed system. As mentioned earlier, a backup drone is configured during the initialization phase for such failure. In this procedure, the LD suddenly becomes unavailable with no prior notification. Thus, a hard handover is made between the backup LD and other SDs as explained in Fig. 9. The unavailability of the LD can be indicated as an SD counts for missed acknowledgments (N_{SD}) from the LD when sending its periodic status reports, likewise, the DMC counts for missing LD periodic status reports (N_{LD}). GPS coordinates are sent in a report to the DMC and then to the Maintenance Unit (MU) for locating the LD and for further actions.

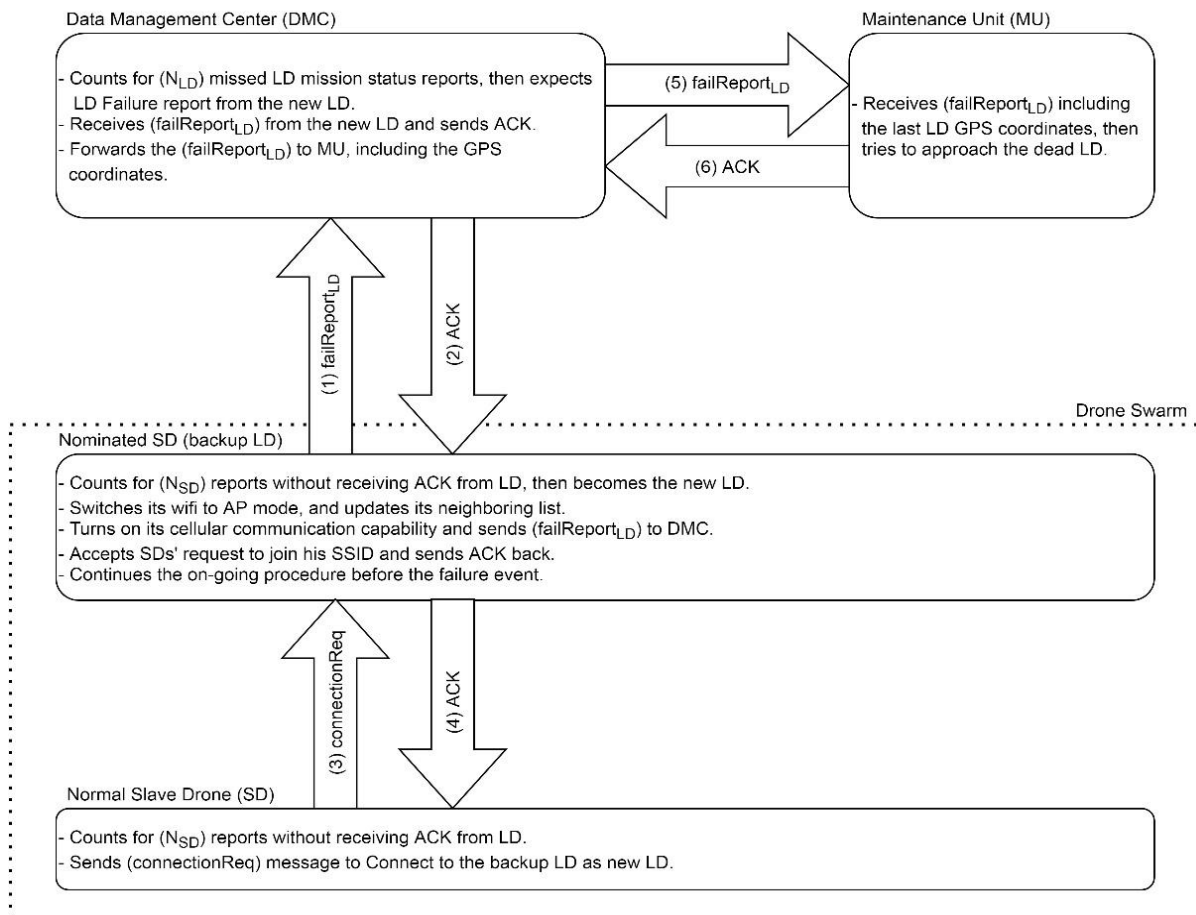


Fig. 9: The LD failure recovery procedure.

2.1.7 The LD Failure Prediction Recovery Procedure

To make the system more robust and reliable, a novel mechanism for predicting failure is proposed. In this scenario, the LD can predict its coming failure according to some status parameters, e.g. hardware temperature or battery level. Consequently, it broadcasts a failure prediction message to the SDs to allow soft-switching which lessens system disturbance during reconfiguration as described in Fig. 10.

The LD temporarily enters the power saving mode and becomes inactive. The backup LD assigns

itself as new LD and other SDs connect to it, then it sends a report to the DMC indicating the failure prediction of the LD. This new failure prediction mechanism involves an enquiring method for the affected node, in our case the LD, where the backup LD enquires the original LD periodically, every (t_p), to trigger it to send a status report that is aggregated with other SD status reports and sent to the DMC. The result of this transit situation is either the LD becomes ready again after rest, or the LD goes off, e.g. flat battery, and then should be announced dead to the swarm and DMC.

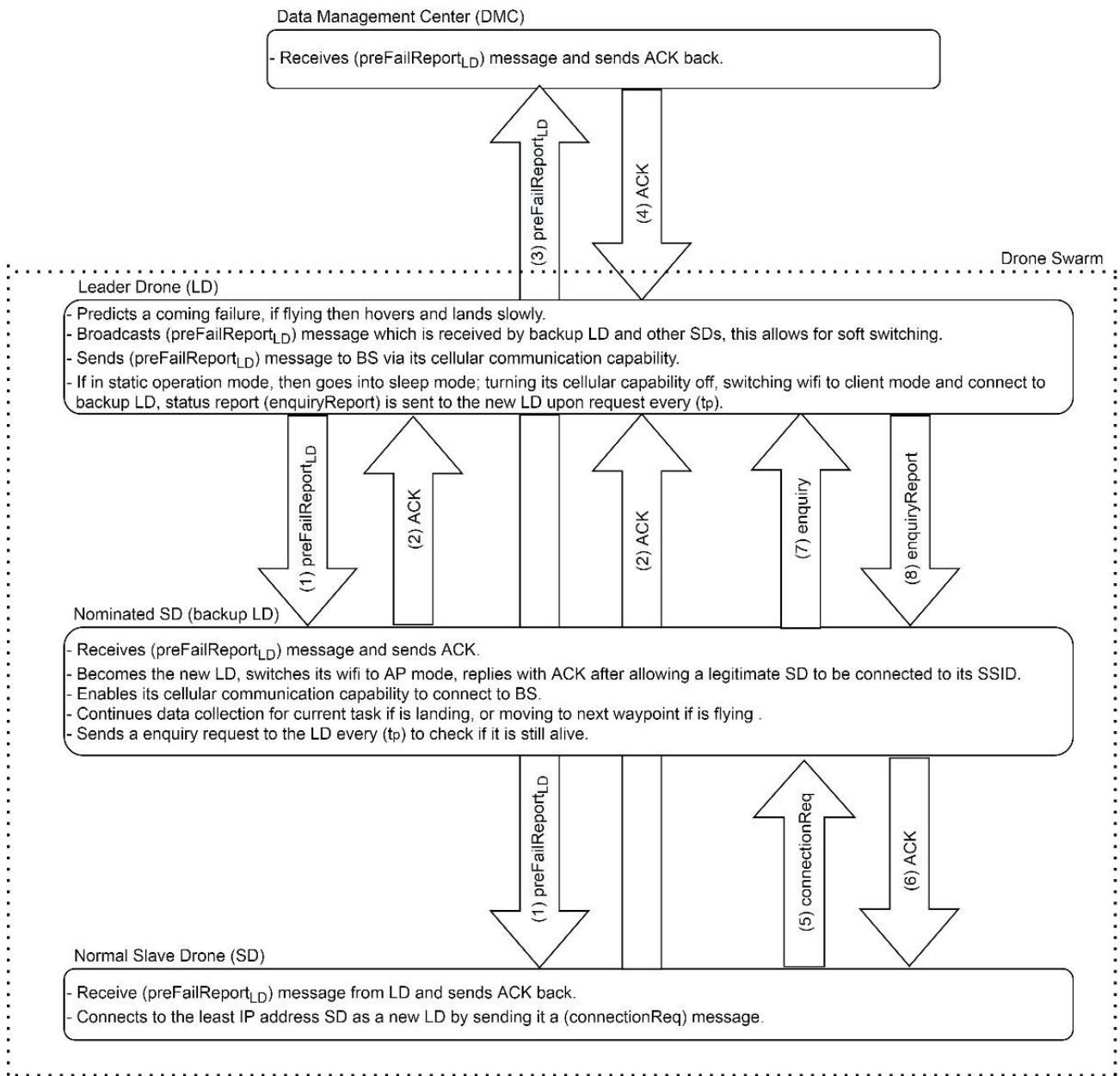


Fig. 10: The LD failure prediction recovery procedure.

2.1.8 The LD Back-to-Work Procedure

While the LD is resting, the reason behind predicting a failure might disappear, e.g. cooling down, allowing the LD to go back to work normally. Therefore, it broadcasts a message within the swarm that indicates its presence so all SDs disconnect from the backup LD and reconnect back to the LD, also a similar back-to-work message is sent to the DMC via its cellular communication capability to update its status there, as illustrated in Fig. 11. This novel failure

prediction mechanism not only allows for continuing carrying out mission tasks by offering a suitable alternative, i.e. backup LD, but also preserves system nodes as it gives a chance for a critical node to go to power-saving mode and rest to mitigate failure causes. If this mechanism is not integrated, the node, e.g. the LD, might continue working in the field till it becomes unavailable, e.g. ignored overheating or a flat battery. Therefore, adopting such a failure prediction mechanism could help preserve system nodes without affecting the system's operational performance.

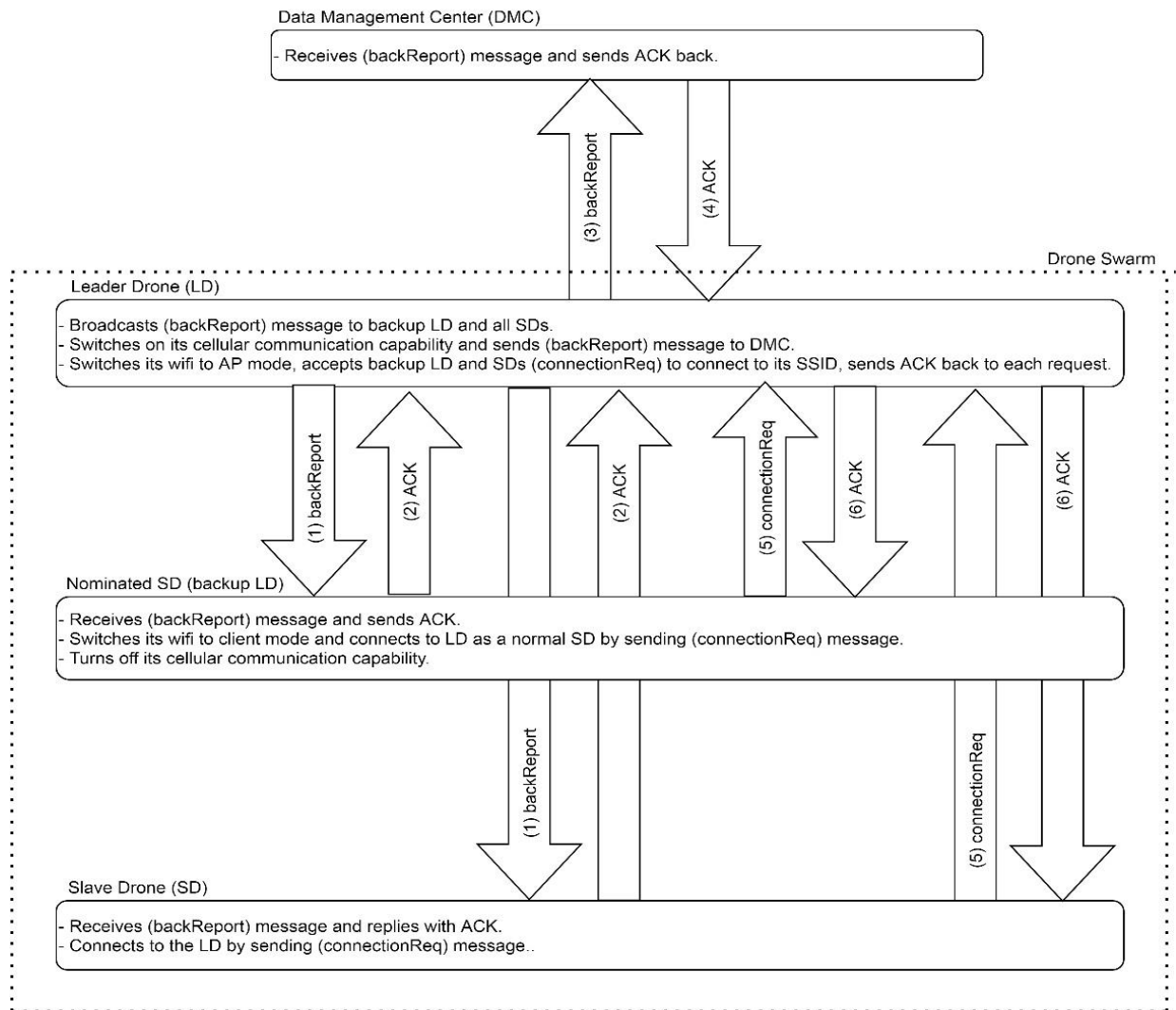


Fig. 11: The LD back-to-work procedure.

2.1.9 The LD Announced Dead Procedure

There is a possibility that the LD is not capable of functioning anymore and the node just simply goes off. The indication, in this case, is the count number of the missing reports (N_P) when the backup LD enquires the

LD to check whether it is alive. If so, then the backup LD stops enquiring and sends a dead report to the DMC including the last status of the LD and its GPS coordinates, and the DMC will forward this report to the MU, as shown in Fig. 12, for locating the LD and further actions.

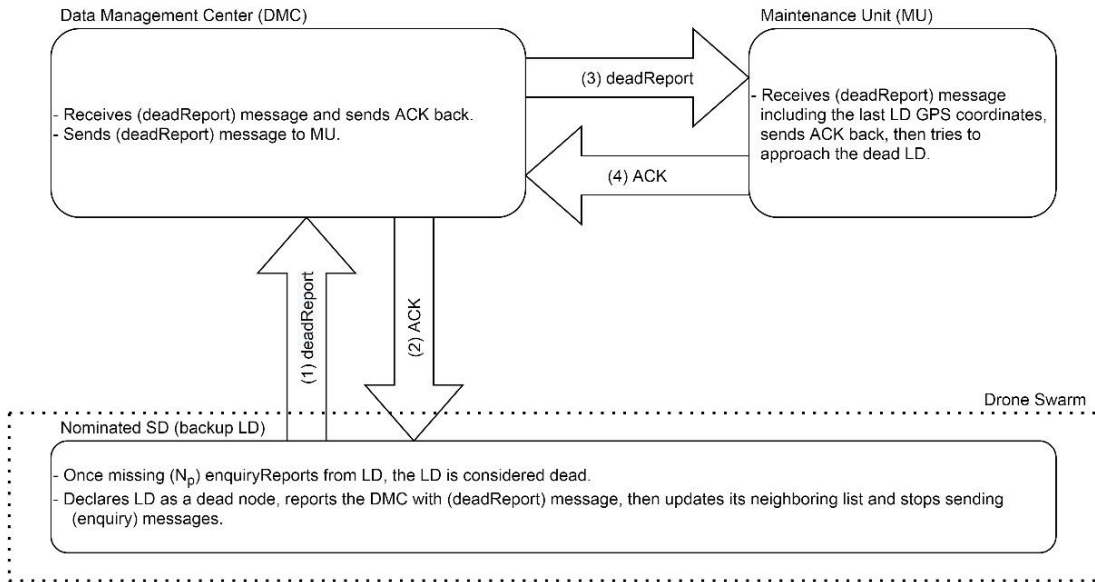


Fig. 12: The LD announced dead procedure.

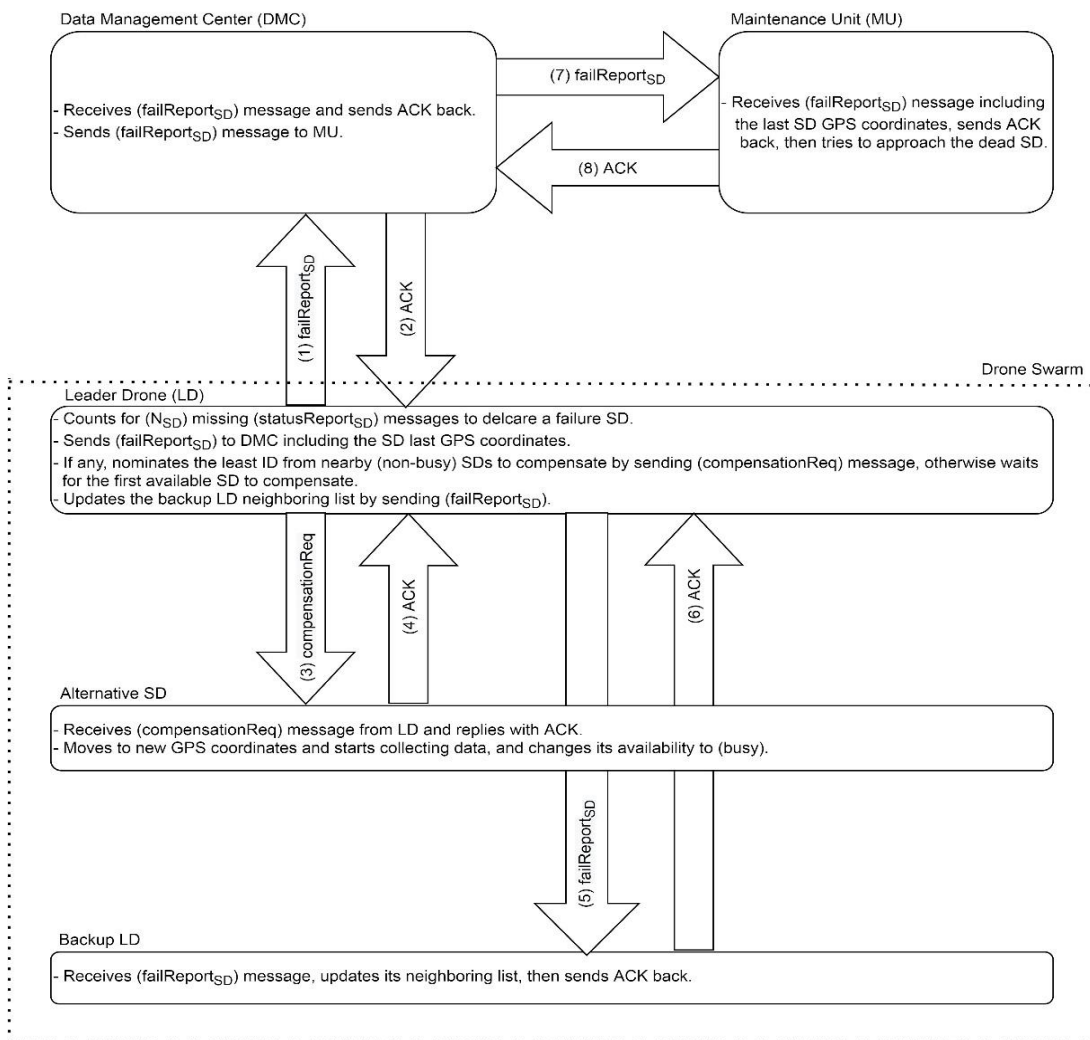


Fig. 13: The SD failure recovery procedure.

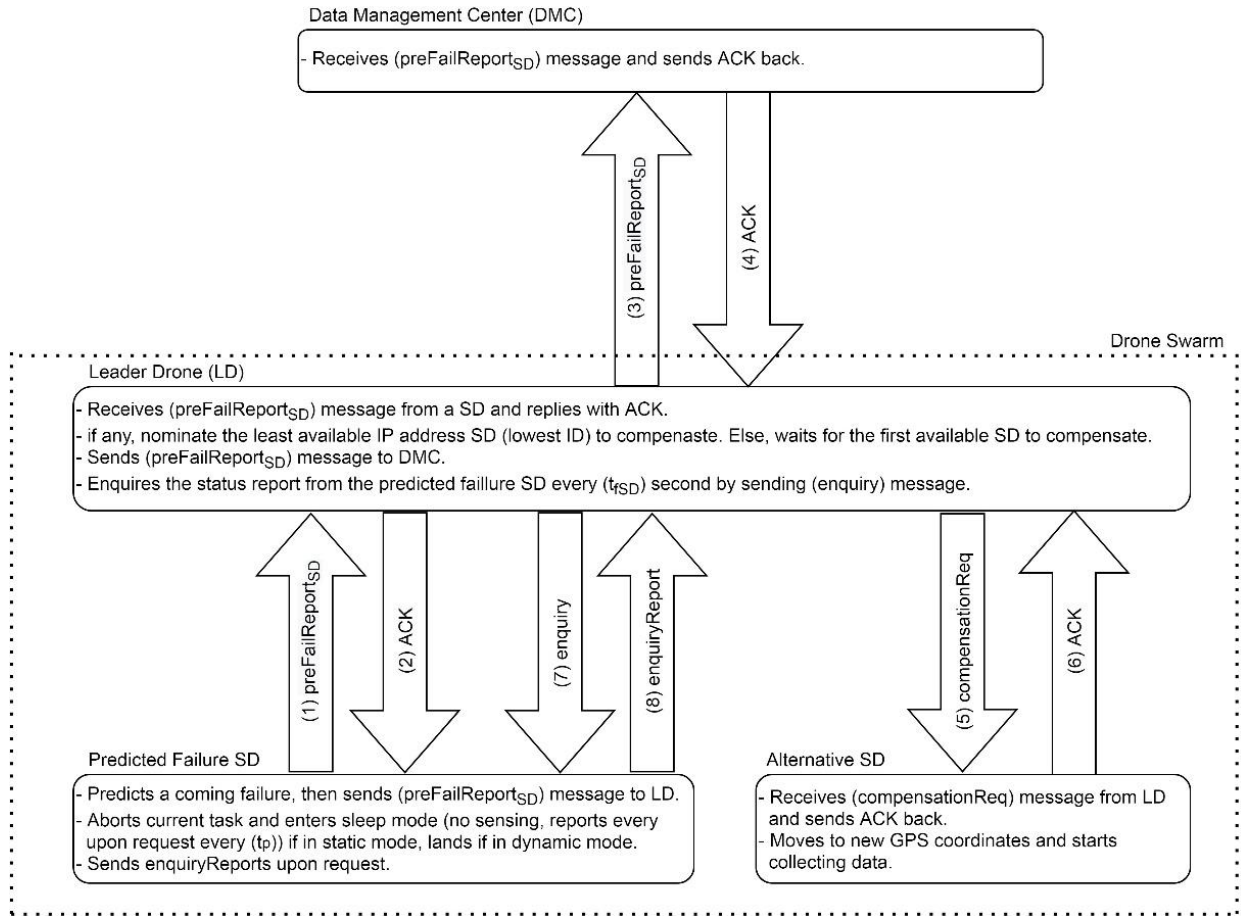


Fig. 14: The SD failure prediction recovery procedure.

2.1.10 The SD Failure Recovery Procedure

Similar to the LD, an SD could confront the same issues that make it unavailable. This case is not as sensitive as losing the LD as other SDs can continue the task. However, in a swarm-based system the tasks are assigned to each member so they work as a team collaboratively, and losing an SD could affect negatively the performance of the system, hence, an alternative SD should be nominated to replace the SD for the current and coming tasks. The LD gives the priority to available non-busy SD to compensate if any, otherwise, it will wait for the first SD to become available and then assign it the task, as in Fig. 13.

2.1.11 The SD Failure Prediction Recovery Procedure

This new mechanism acts the same as for the LD, where an SD predicts a failure and sends a specific message to the LD informing it of its status and goes into the power-saving mode to mitigate the causes of

failure. The LD, in turn, looks for an alternative SD for compensation as well as starts enquiring the affected SD for its status periodically, as described in Fig. 14. Similar to the LD prediction failure procedure, the SD is resting temporarily and this scenario ends in one of two cases; either the SD comes back to work or becomes a dead node.

2.1.12 The SD Back-to-Work Procedure

In this scenario, an SD recovers and becomes ready to perform a task. So, the SD sends a message to the LD indicating its return which will be forwarded to the DMC, see Fig. 15.

2.1.13 The SD Announced Dead Procedure

The other possibility is when a resting SD goes off. In this case, the LD will not receive enquiry status reports and consider the SD as a dead node, then inform the DMC as shown in Fig. 16.

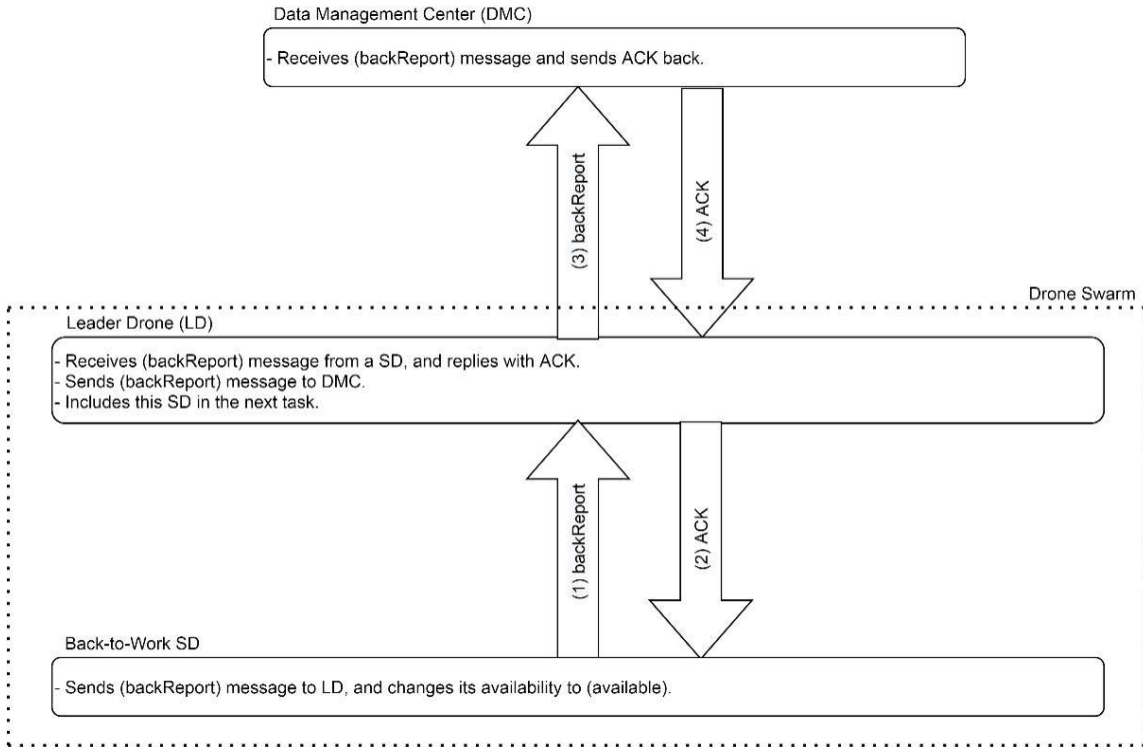


Fig. 15: The SD back-to-work procedure.

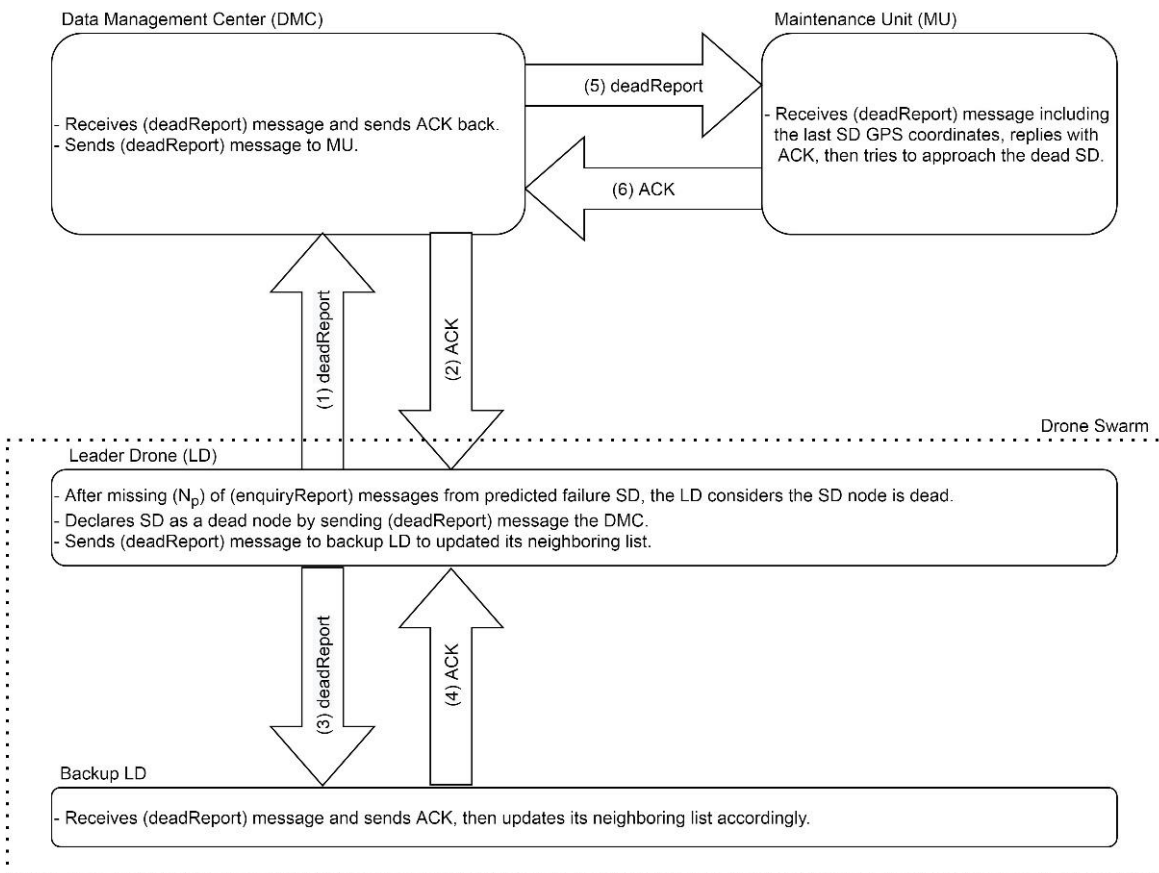


Fig. 16: The SD announced dead procedure.

2.1.14 The Proposed System-Specific Messages

In general, there are 18 new proposed messages in total that are used by the proposed UAV swarm-based system and are shown in Table. 1, where 8 messages are used during the normal operation phase and the other 10 messages are intended for failure

handling. It is noticed from Table. 1, that the system messages are small in size and each message, or command, has certain fields to be informative. The (x,y) pair represents the GPS coordinates, while the (z) expresses the altitude. The symbol (n) represents the number of SDs in the swarm.

Table. 1: System messages and their fields and size

Scenario	Sq.	Command name	Command Contents						Command Size (Byte)
Initialization state	1.	swarmReady	type	id _{UAV}					2
	2.	launch	type						1
Flying state	3.	moveToWaypoint	type	formation type	distance	Z _{LD}	(x,y) _{LD}		13
	4.	land	type	id _{SD}	(x,y) _{SD}				10
Flying/landing states	5.	statusReport _{SD}	type	id _{SD}	(x,y) _{SD}	battery level	temperature	available	13
Flying/landing states	6.	statusReport _{LD}	type	id _{LD}	(x,y) _{LD}	battery level	temperature	swarm status	12+12*(n)
landing state	7.	caseReport	type	id _{SD}	(x,y) _{SD}	case severity	Scanned ID		500
Flying/landing states	8.	ack	type	id _{UAV}					2
LD failure	9.	failReport _{LD}	type	id _{LD}	Z _{LD}	(x,y) _{LD}			12
	10.	connectionReq	type	id _{SD}					2
	11.	preFailReport _{LD}	type	id _{LD}	Z _{LD}	(x,y) _{LD}			12
	12.	enquiry	type						1
	13.	enquiryReport	type	id _{UAV}	(x,y)	battery level	temperature		12
	14.	backReport	type	id _{UAV}	(x,y)	battery level	temperature		12
	15.	deadReport	type	id _{dead_UAV}	Z _{dead_UAV}	(x,y) _{dead_UAV}			12
SD failure	16.	failReport _{SD}	type	id _{SD}	Z _{SD}	(x,y) _{SD}			12
	17.	compensationReq	type	id _{SD}	(x,y) _{SD}				10
	18.	preFailReport _{SD}	type	id _{SD}	Z _{SD}	(x,y) _{SD}			12

3. The Proposed System Mathematical Evaluation

There are many communication and networking technologies to select from, however, adopting certain technologies could be application-dependent, or availability-dependent in the area of application [21-23]. Table. 2 explains the adopted technology for the proposed system.

After the system has been described, a mathematical model checking for the proposed system performance in different scenarios was performed using the following general equations [24-26].

$$Latency = 2 * Node\ delay + Network\ delay \tag{1}$$

$$Network\ delay = \frac{Packet\ length}{Data\ rate} + \frac{Distance}{Speed} \tag{2}$$

$$Throughput = \frac{File\ size}{Latency} \tag{3}$$

Equation parameters could be substituted by real values of currently existing protocols that could be adopted so that approximate figures can be obtained. Table. 3 shows the values that can be used in these equations.

Let us consider a simple scenario to apply equations (1) to (3) and evaluate system performance for that given scenario. The selected scenario is the formation procedure, as shown in Fig. 5, which includes two application-specific messages; a broadcast (move To Way point) message and a unicast (ACK) message.

The formation scenario can be thought of from a networking point of view to show all background

messages too and consider the entire traffic when calculating the scenario latency and throughput. However, the formation procedure timing diagram, which needs a Wi-Fi connection only, will be brought to this section for the sake of explaining how to evaluate the system mathematically and calculate the latency and throughput for such scenarios.

It can be noticed that although only two application-specific messages are exchanged, other background networking messages are transacted. The Request to Send/Clear to Send (RTS/CTS) is used by the 802.11 wireless networking protocol as an option to reduce frame collisions introduced by hidden node problems, these packets are transferred at the basic data rate of the protocol used.

Table. 2: Networking protocols adopted by the system.

Protocol	Abbreviation	Description
Dynamic Host Configuration Protocol version 6	DHCPv6	Automatically provides a host with network configurations, e.g. the IP address, subnet mask, and gateway.
User Datagram Protocol	UDP	Transport layer protocol
Internet Protocol version 6	IPv6	Network layer protocol
Institute of Electrical and Electronics Engineers 802.11a	IEEE 802.11a	Transmitting data over a wireless network among different Drones
Worldwide Interoperability for Microwave Access	WiMAX	Transmitting data over broadband cellular networks between Leader Drone and DMC

Table. 3: The adopted network parameters and values.

Parameter	Value	
Node delay	0.0001 (10000 packet/s)	
Packet length	Various packets	Packet dependent (refer to Table. 1)
	RTS	20 byte
	CTS / ACK	14 byte
Data rate	Wifi (basic)	6Mbps
	Wifi (normal)	54Mbps
	WiMAX	75Mbps
Distance	UAV-to-UAV	12 meters
	LD-to-DMC	1 km
Propagation speed	3×10^8 m/s	
DIFS	0.3 ms	
SIFS	0.02 ms	

Table. 4: Calculated latency and throughput for each scenario.

No.	Scenario name	Data transferred (bytes)	Latency (ms)	Throughput (Kbps)
1	Initialization Procedure	2017	22.81	707.41
2	Formation Procedure	165	4.35	189.5
3	Operation Procedure (dynamic mode)	765 (Wi-Fi) (1s)	26.25	145.81
		5 (wimax) (1s)	85.42	0.058
4	Deployment Procedure	120	5.4	220.77
5	Operation Procedure (static mode)	2 Mega (1s) (wifi)	6.39 s	2.09 Mbps
		2 Mega (1s) (wimax)	5.94 s	2.24 Mbps
6	LD Failure Recovery Procedure	14 (wifi)	6.35	17.64
		24 (wimax)	170.57	1.13
7	LD Failure Prediction Recovery Procedure	123 (wifi)	5.23	188.15
		12 (wimax)	85.29	1.13
8	LD Back-to-Work Procedure	112 (wifi)	6.4	140
		12 (wimax)	85.29	1.13
9	LD Announced Dead Procedure	24 (wimax)	170.58	1.13
10	SD Failure Recovery Procedure	22 (wifi)	1.45	15.17

		24 (wimax)	170.58	1.13
11	SD Failure Prediction Recovery Procedure	35 (wifi)	2.21	15.84
		12 (wimax)	85.29	1.13
12	SD Back-to-Work Procedure	12 (wifi)	0.91	13.19
		12 (wimax)	85.29	1.13
13	SD Announced Dead Procedure	12 (wifi)	0.91	13.19
		24 (wimax)	170.58	1.13

Additionally, the WLAN Acknowledgement (ACK) message is used to provide reliability when transferring data over an unreliable medium. Furthermore, the Distributed Inter-Frame Space (DIFS) and Short Inter-Frame Space (SIFS) time spaces are included. Now, equations from (1) to (3) could be used to calculate the throughput and latency for the formation procedure.

The throughputs and latencies for previously mentioned scenarios are calculated and the results are summarized in Table. 4. This is a mathematical evaluation and the resulting values are approximate to what is expected in reality. This is because when calculating the results, it is assumed that the proposed system is operating in ideal circumstances, e.g. no external noise, no network congestion, no signal attenuation, etc. Therefore, the proposed approach needs to be evaluated using a developed software tool to get closer results to reality and to prove the feasibility and applicability of the system.

Each system procedure was considered for this mathematical evaluation that was done using Microsoft Excel, where the network messages were considered for calculations along with timing spaces, i.e. DIFS, SIFS, etc., to calculate the latency and throughput for each communication technology used, i.e. WLAN and WiMAX sides, to find out approximate values that provide an estimated overview of the system performance.

4. Conclusion

The proposed formation control and failure recovery mechanisms offer a balance between complexity, flexibility, and robustness. The leader-follower approach simplifies formation control while enabling adaptability to various scenarios. The combined failure detection and dynamic task allocation strategies facilitate rapid and efficient recovery from both predicted and unexpected failures. While the system demonstrates strong performance in

simulations, continuous improvement is essential. Future research should focus on:

- **Decentralized Control:** Investigating decentralized control approaches to further enhance swarm resilience to LD failures.
- **Communication Optimization:** Developing adaptive communication strategies to minimize overhead and improve efficiency, especially in larger swarms.
- **Advanced Failure Prediction:** Exploring more sophisticated failure prediction models using machine learning and data analytics to anticipate failures more accurately.
- **Integration with Advanced Control:** Integrating failure management with more sophisticated formation control algorithms to optimize swarm behavior in dynamic and unpredictable environments.

By addressing these areas, the proposed system can be further refined and optimized for real-world deployment, enabling the realization of a truly robust and reliable UAV swarm-based Smart Metering Infrastructure.

Conflict of interest

The authors declared 'No conflict of interest'.

References

- [1] K. C. Aleksander, "Military use of unmanned aerial vehicles—a historical study," *Safety & Defense*, Vol. 4, pp. 17-21, 2018.
<https://doi.org/10.37105/sd.4>
- [2] J. Kim, S. Kim, C. Ju, and H. I. Son, "Unmanned aerial vehicles in agriculture: A review of perspective of platform, control, and applications," *Ieee Access*, Vol. 7, pp. 105100-105115, 2019.
<https://doi.org/10.1109/ACCESS.2019.2932119>

- [3] M. Lyu, Y. Zhao, C. Huang, and H. Huang, "Unmanned aerial vehicles for search and rescue: A survey," *Remote Sensing*, Vol. 15, No. 13, art. no. 3266, 2023.
<https://doi.org/10.3390/rs15133266>
- [4] N. Guimarães, L. Pádua, P. Marques, N. Silva, E. Peres, and J. J. Sousa, "Forestry remote sensing from unmanned aerial vehicles: A review focusing on the data, processing and potentialities," *Remote Sensing*, Vol. 12, No. 6, art. no. 1046, 2020.
<https://doi.org/10.3390/rs12061046>
- [5] K. Peng, J. Du, F. Lu, Q. Sun, Y. Dong, P. Zhou, et al., "A hybrid genetic algorithm on routing and scheduling for vehicle-assisted multi-drone parcel delivery," *IEEE Access*, Vol. 7, pp. 49191-49200, 2019.
<https://doi.org/10.1109/ACCESS.2019.2910134>
- [6] M. Qassab and Q. Ali, "A comprehensive survey on current literature, standards, applications and projects of self-organizing aerial ad hoc network (aanet) in smart cities," *Current Chinese Computer Science*, Vol. 1, No. 2, art. no. e030621191583, 2021.
<http://dx.doi.org/10.2174/2665997201666210218232040>
- [7] W. Chen, J. Liu, H. Guo, and N. Kato, "Toward robust and intelligent drone swarm: Challenges and future directions," *IEEE Network*, Vol. 34, No. 4, pp. 278-283, 2020.
<https://doi.org/10.1109/MNET.001.1900521>
- [8] G. Skorobogatov, C. Barrado, and E. Salamí, "Multiple UAV systems: A survey," *Unmanned Systems*, Vol. 8, No. 2, pp. 149-169, 2020.
<https://doi.org/10.1142/S2301385020500090>
- [9] F. S. Alsharbaty and Q. I. Ali, "An enhanced industrial wireless communication network for hard real time performance substation automation purposes," *Al-Rafidain Engineering Journal (AREJ)*, vol. 27, No. 2, pp. 216-226, 2022.
<https://doi.org/10.33899/rengj.2022.133860.1173>
- [10] C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," in *Proceedings of the 14th annual conference on Computer graphics and interactive techniques*, Vol. 27, No. 4, pp. 25-34, 1987.
<https://doi.org/10.1145/37402.37406>
- [11] S. J. Chung, A. A. Paranjape, P. Dames, S. Shen, and V. Kumar, "A survey on aerial swarm robotics," *IEEE Transactions on Robotics*, Vol. 34, No. 4, pp. 837-855, 2018.
<https://doi.org/10.1109/TRO.2018.2857475>
- [12] Q. Ibrahim and M. Qassab, "Theory, Concepts and Future of Self Organizing Networks (SON)," *Recent Advances in Computer Science and Communications (Formerly: Recent Patents on Computer Science)*, Vol. 15, No. 7, art. no. e190522190934, 2021.
<http://dx.doi.org/10.2174/2666255814666210201102326>
- [13] H. T. Do, H. T. Hua, M. T. Nguyen, C. V. Nguyen, H. T. Nguyen, H. T. Nguyen, et al., "Formation control algorithms for multiple-uavs: a comprehensive survey," *EAI Endorsed Transactions on Industrial Networks and Intelligent Systems*, Vol. 8, No. 7, pp. e3, 2021.
<https://doi.org/10.4108/eai.10-6-2021.170230>
- [14] Q. Ouyang, Z. Wu, Y. Cong, and Z. Wang, "Formation control of unmanned aerial vehicle swarms: A comprehensive review," *Asian Journal of Control*, Vol. 25, No. 1, pp. 570-593, 2023.
<https://doi.org/10.1002/asjc.2806>
- [15] K. K. Oh, M. C. Park, and H. S. Ahn, "A survey of multi-agent formation control," *Automatica*, Vol. 53, pp. 424-440, 2015.
<https://doi.org/10.1016/j.automatica.2014.10.022>
- [16] Y. Liu, J. Liu, Z. He, Z. Li, Q. Zhang, and Z. Ding, "A survey of multi-agent systems on distributed formation control," *Unmanned Systems*, Vol. 12, No. 15, pp. 913-926, 2024.
<https://doi.org/10.1142/S2301385024500274>
- [17] Q. Chen, Y. Wang, Y. Jin, T. Wang, X. Nie, and T. Yan, "A Survey of An Intelligent Multi-Agent Formation Control," *Applied Sciences*, Vol. 13, No. 10, art. no. 5934, 2023.
<https://doi.org/10.3390/app13105934>
- [18] F. Saffre, H. Hildmann, H. Karvonen, "The Design Challenges of Drone Swarm Control", *Lecture Notes in Computer Science*, Vol. 12767, pp. 408-426, 2021.
https://doi.org/10.1007/978-3-030-77932-0_32
- [19] O. I. Abiodun, A. Jantan, A. E. Omolara, K. V. Dada, N. A. Mohamed, and H. Arshad, "State-of-the-art in artificial neural network applications: A survey," *Heliyon*, Vol. 4, No. 11, art. no. e00938, 2018.
<https://doi.org/10.1016/j.heliyon.2018.e00938>

- [20] V. François-Lavet, P. Henderson, R. Islam, M. G. Bellemare, and J. Pineau, "An introduction to deep reinforcement learning," *Foundations and Trends in Machine Learning*, Vol. 11, pp. 3-4, 2018. <https://doi.org/10.1561/22000000071>
- [21] S. L. Qaddoori and Q. I. Ali, "An efficient security model for industrial internet of things (IIoT) system based on machine learning principles," *Al-Rafidain Engineering Journal (AREJ)*, Vol. 28, No. 1, pp. 329-340, 2023. <https://doi.org/10.33899/rengj.2022.134932.1191>
- [22] Q. I. Ali, "Performance Evaluation of WLAN Internet Sharing Using DCF & PCF Modes," *The Arab International Journal of Information Technology*, Vol. 1, pp. 38-45, 2009. [\[Cross Ref\]](#)
- [23] S. A. Yasser, M. Abdul-Jabbar, and Q. I. Ali, "Design and Performance Evaluation of Lattice Daubechies Wavelet Filter Banks for Less Complex Cognitive Transceivers," *Al-Rafidain Engineering Journal (AREJ)*, Vol. 25, No. 1, pp. 61-69, 2020. <https://doi.org/10.33899/rengj.2020.126799.1021>
- [24] Q. I. Ali, "Green communication infrastructure for vehicular ad hoc network (VANET)," *Journal of Electrical Engineering*, Vol. 16, pp. 10-10, 2016. [\[Cross Ref\]](#)
- [25] Q. Ibrahim, "Design & Implementation of High Speed Network Devices Using SRL16 Reconfigurable Content Addressable Memory (RCAM)," *International Arab Journal of e-Technology*, Vol. 2, No. 2, pp. 72-81, 2011. [\[Cross Ref\]](#)
- [26] S. Lazim Qaddoori and Q. I. Ali, "An embedded and intelligent anomaly power consumption detection system based on smart metering," *IET Wireless Sensor Systems*, Vol. 13, No. 12, pp. 75-90, 2023. <https://doi.org/10.1049/wss2.12054>



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