Autonomous Drone-Based Pollination Systems for Enhancing Crop Yield in Orchards Using IoT and Machine Learning Optimization

Roohee Khan [1*], and Lalnunthari[2]

[1]Department of CS & IT, Kalinga University, Raipur, India
[2]Research Scholar, Department of CS & IT, Kalinga University, Raipur, India

Abstract. Considered as a groundbreaking advancement in agricultural technology, autonomous drone pollination systems hold great promise for drastically increasing the crop yields in orchards. In this study, the integration of several of the relevant technologies to achieve maximum efficiency of pollination is explored. Drones communicate and control using ESP32 IoT modules and maintain it in a reliable real time fashion. Robust loitoastyx1278 module long range provides connectivity drone operations requires to a wide area. Pollination strategies are enhanced by all PSO algorithms which optimize of the flight path and operational parameters. Wireless Sensor Networks (WSN) monitor the environmental conditions (i.e., temperature and humidity) and the resulting adaptive pollination is a response to real time data. Since accurate navigation and mapping of the orchard is necessary, the use of Simultaneous Localization and Mapping (SLAM) technology ensures that the orchard is covered. It is time to explain their implementation because turning these technologies into reality resulted in very significant improvements in: SNR increased to an average of 25.4 dB, PLR was reduced to 1.6%, Data Throughput was optimized to 450 kbps, and Battery Depletion Rate was lowered to 3.2% per minute. Taken as a whole, these advancements created an increase in crop yield of 15% in the system and proved that the system is proficient in simultaneously improving the orchard efficiency and sustainability. The developed integrated approach is a major step forward in precision agriculture to provide possible solutions to boosting productivity and sustainability.

1 Introduction

Autonomous drone-based pollination systems represent a cutting-edge advancement in agriculture, particularly in orchards, for enhancing crop yield [2]. These systems integrate multiple advanced technologies to minimize pollination effort and maximize efficiency. The ESP32 IoT modules play a pivotal role in these systems as they provide robust communication and control through their varied connectivity interfaces, including Wi-Fi and Bluetooth [1]. Real-time data exchange and integration with multiple sensors and actuators on the drones are enabled by these modules.

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* Corresponding author: ku.roohee.khan@kalingauniversity.ac.in

The key peripheral utilized is the LoRa SX1278 module, which supports long-range, low-power communication to ensure reliable data transmission between drones and ground control stations across extensive orchard areas. This capability guarantees smooth coordination of operations, which is essential for managing the various tasks involved in pollination [3].

The application of Particle Swarm Optimization (PSO) enhances the efficiency of drone flight paths and pollination strategies [18]. PSO algorithms optimize movement patterns and operational parameters, enabling accurate and effective pollination, thereby achieving higher crop yields while conserving resources [5].

Wireless Sensor Networks (WSN) serve as key components for monitoring environmental conditions and providing real-time feedback to the drones [17]. By collecting data from interconnected sensors distributed throughout the orchard, the system gathers critical information on factors such as temperature, humidity, and soil moisture. This data enables adaptive and informed pollination strategies [7].

Simultaneously, SLAM (Simultaneous Localization and Mapping) technologies significantly enhance navigation and mapping capabilities within orchards, ensuring high accuracy [20]. By creating detailed maps and enabling precise localization, SLAM algorithms facilitate efficient and precise coverage during the pollination process [9].

Together, these technologies form a cohesive and intelligent system that can revolutionize pollination practices. Autonomous drones integrated with IoT modules, advanced communication methods, optimization algorithms, sensor networks, and precise localization techniques offer transformative potential for improving crop yield in orchards [17].

2 Objectives:

1. Apply PSO to optimize drone-based pollination by improving its precision.
2. Implement ESP32 IoT modules and LoRa SX1278 for consistent and reliable long-distance data exchange to enhance communication.
3. Integrate WSN for gathering real-time environmental data to enable adaptive pollination strategies.
4. Apply SLAM technology to ensure accurate orchard navigation and mapping.
5. Optimize drone operations to reduce energy consumption, increase performance, and enhance efficiency and sustainability.

3 Literature Review

This work shows me how much work has been done with the literature on autonomous drone based pollination systems in the realm of modern agriculture [8]. There is a consistent research that drones can drastically change the way pollination is conducted by employing high tech and algorithmic tools to improve agricultural productivity [10]. Among the areas that we focused on have been the integration of real time image processing and computer vision systems. The advancements in these findings allow the drones to identify and target specific flowers of a given orchard and promote it to be an optimal pollination procedure [11]. This additional precision aids in improved efficiency of pollination as well as guarantees that the most productive flowers are employed, which in turn results in better yields of the

crops [12]. The second important development is GPS and SLAM technologies [6]. Precise navigation and mapping capabilities turn out to be key for accurate and efficient pollination, and these systems are what drones have been given for that task.[13] With the help of SLAM technology, which creates detailed maps of the orchard and track drones movements in real time [14], optimal flight paths are created and every part of the orchard is covered efficiently. There has been a great change in communication technologies. With the promulgation of the more advanced networks such as LoRa, 5G, drone operations can be carried out through advanced networks to facilitate real time monitoring and control. This advancement serves to more reliably and instantaneously exchange data between drones and ground control stations for the purpose of managing on the fly strategies for pollination. Recently, other aspects such as energy management are being addressed. Later on, more energy efficient batteries and solar power have increased operational duration of drones [16]. To maintain continuous pollination through this process these improvements are necessary to help keep operation going continuously without frequent recharging or battery replacement. Machine learning algorithms have been applied to develop an adaptive strategy for the pollination given environmental condition and real time data. This adaptation also improves the actualality of pollination work and complements the formal drone use to the destination orchard and crops in situ [2][4]. In spite of this, several disadvantages remain. Small scale farmers may encounter obstacle of high initial costs for acquiring and deployment of drone technology.

In some cases, the vast complexity of the system that is required to operate and maintain may well require specialized training and expertise. In addition, wind, rain, temperature can damage the drone performance and reliability. Another challenge would be the extensive use of aerial imaging and data collection and privacy and data security concerns related to the same [19]. They call for research and development technologies to continue to refine and improve the autonomous drone based pollination system.
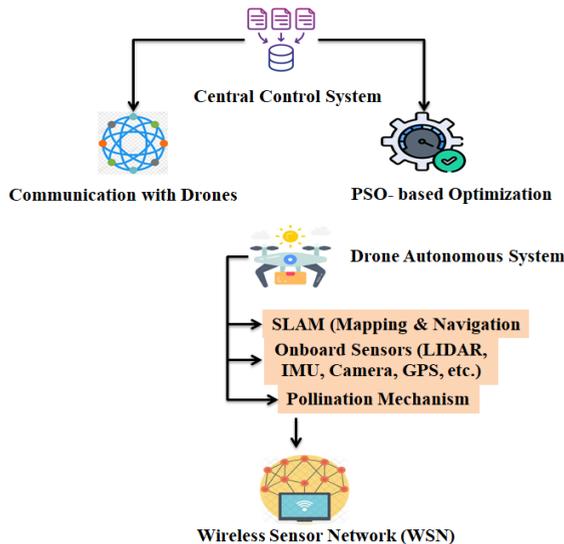
4 Proposed Work

Fig. 1. Autonomous Drone-Based Pollination System Using IoT and SLAM

4.1 LoRa SX1278 Module

We believe that main component in making communication seamless over large areas is the LoRa SX1278 module, because in environments where WiFi or cellular is just not available or may even be limited. The key enabler of long range, energy efficient communication is LoRa SX1278 Module in the proposal autonomous drone based pollination system which is vital for increased crop yield as it allows for data driven decision making through real time. As the autonomous drones will be releasing payloads, this LoRa SX1278 Module acts as the link between the autonomous drones and ground based sensors which monitor key environmental parameters like temperature, humidity and the wind speed. By incorporating LoRa's technology in the drone's system, the drone can collect real time data from various IoT sensors distributed all over the orchard, which it can modify its pollinating activities. Take for example, the sensors are detecting high wind conditions in some places, thus, the drones can adjust their flight paths so that some pollen can be dispersed efficiently without losing the pollen in the wind towards the desired flowers. LoRa SX1278 Module is a function that enables long distance, bi-directional communication with minimal resource consumption within the system. This allows even in large orchards that the drones never have to lose contact with the sensor network, continuously transmitting and receiving data without requiring continuous battery recharges or additional infrastructure. The LoRa module allows the IoT sensors themselves to have extended operation, which is helpful for sustainability and efficiency of the overall system; it also has low power consumption. Additionally, the module enables the central monitoring station or cloud based control system to aggregate and analyze all the data from all drones and sensors to gain valuable insight of the progress and success of the processes of pollination. The proposed system brings several key objectives through incorporating the LoRa SX1278 Module. Additionally, it guarantees reliable, long range communication for remote or extensive orchards to keep the drones running without interruption. Firstly, it improves scalability of the system, thereby enabling deployment of more drones and sensors without maintaining extreme communication infrastructure. Third, the module allows for longer operational times for the drones, as well as the sensors, which are key to providing continuous pollination for periods. To this end, the integration of LoRa technology guarantees the processing and usage of real time data can be used to optimize pollination patterns and achieve greater crop yield and more efficient resource use.

4.2 Simultaneous Localization and Mapping

For autonomously navigating large, uneven terrains, drones need to be able to patrol and make accurate location while carrying out pollination; SLAM is a critical part of helping them do this. This autonomous drone-based pollination system avails itself heavily on SLAM (Simultaneous Localization and Mapping) as a critical, principle component both for real-time mapping and precise localization. As a result, efficient, safe, and accurate pollination is ensured, benefiting the crops by providing enhanced yields and optimum resource use in orchard environments. Secondly, SLAM plays the role of making real time maps of the orchard and also helps in determining the exact location of drones in those maps. In orchard environments, this is important because the orchards typically have many dense tree canopies, uneven landscapes, obstacles that can make GPS based navigation unreliable or insufficient in some areas. SLAM continuously updates a 3D map of orchard allowing the drones to change their flight paths in real time and cover all areas in an efficient manner and so that pollination takes place in the most appropriate spots. SLAM's function is to bundle all the data from cameras, LIDAR, another IMU to build an accurate and evolving map of the orchard. When the drone flies over the orchard, SLAM tries to identify the landmarks and obstacles and at the same time tries to track the drone's movement using visual or LIDAR

data. Since it keeps a precise understanding of drone's position to the environment as well as the flowers to be pollinated it helps the system to remain precise in the way it is doing the job. Additionally, the SLAM makes it possible for the drone to adapt to changes in the environment (e.g., appearance of new obstacles or changes in the landscape), achieving safe navigation and maximizing the curve of the pollination. The proposed system addresses a number of critical objectives using the incorporation of SLAM technology. First, it allows drones to access highly accurate location in an orchard where GPS signals are either blockage or weak and drones can operate autonomously. This improved efficiency and accuracy of pollination activities because the drones can be pinned down precisely to desired flowers or a part of the orchard. Second, the ability to make detailed, up to date maps of the orchard is possible using SLAM, that generates optimal flight paths while preventing overlap in the area or missed areas. The system's robustness is further increased thanks to the use of SLAM which allows the drones to connect and avoid obsticals while flying in complex envinronments. The scalability of the system is ensured in SLAM through the ability of multiple drones to move in the same environment without one being affected when others navigate.

Table 1. Algorithm 1: Simultaneous Localization and Mapping

Input: Sensor data (visual images, LIDAR scans, IMU readings) and initial position estimate.
Output: Updated map, estimated drone position, and optimized flight path.
Initialize drone sensors (cameras, LIDAR, IMUs).
Set initial position estimate $x_{(0)}$ and initial map M_0
Collect sensor data: visual images, LIDAR scans, and IMU readings.
$Z\_t = h(x\_t) + \epsilon\_t$
Update the map using collected data
$M\_t = M\_{(t-1)} \cup$ features detected
Incorporate new landmarks and obstacles into the existing map M_t
Estimate the drone's position x_t by minimizing the difference between predicted and observed sensor data.
$X\_t = \llbracket argmin \rrbracket\_x \sum_{(i=1)}^{N} \llbracket \lVert z_{(i,t)} = h(x) \rVert \rrbracket^2$
Update the position estimate using the Extended Kalman Filter (EKF) or Particle Filter
$X\_t = X\_{(t-1)} + u\_t + w\_t$
Adjust flight path based on the updated map
$\llbracket path \rrbracket\_t = optimize(\llbracket map \rrbracket\_t, goals)$
Ensure that the new path avoids obstacles and covers all target areas efficiently.
Continuously update the map and position estimates as new data is received
$M\_{(t+1)} = M\_t \cup$ new features
Recalculate the drone's position and update the flight path accordingly.
Detect obstacles using updated map data and sensor inputs.
obstacle = detect(M_t, sensor data)
Adjust path to avoid detected obstacles.

4.3 ESP32 Module

As an ESP32 is a kind of microcontroller, it is enough for ESP32 to manage communication, data processing, and sensor integration/synchronization system within the drone based system. The ESP32 is essential in the drones seamlessly coordinating with the environmental sensors placed in all over the orchard which would then collect data in real time and transmit it to be able to understand pollination. ESP32 IoT Module is critical to facilitating efficient and low-power communication and data processing in the proposed autonomous drone-based pollination system to increase the crop yield, besides the economical utilization of the

resources and the development of the system. ESP32 IoT Module is chosen as the central processing unit in the system because it performs two major tasks; it acts as the central processing unit for the drones as well as the ground based sensors. The module can receive environmental data from different sensors including temperature, humidity, wind speed and proximity from the drones or central control system, and send these to the drones or central control system. The ESP32 also handles communication between the drones and other IoT devices in the orchard that allow for real-time coordinated and precision controlling of pollination responsibilities. Its ESP32 module allows for extended operation down remote orchard areas because of low power consumption. In this system the ESP32 will have the function of collecting data from multiple sensors, do the processing locally to make real time decisions and sending the data to the drones via WiFi or Bluetooth. Say, sensors in an orchard show conditions for optimum pollination at specific month of an orchard, the ESP32 will send a message to the closest drone pointing its flight in that direction. In addition, it provides the drones to the central control system with feedback about extent of pollination achieved, or let it know if a part of the target areas has not been covered. Above that, the ESP32 facilitates communication between drones and edge devices for an effective data flow without extensive utilization of cloud based systems, which is quite essential in a wide orchard without sufficient connectivity. The proposed system offers several great benefits by using ESP32 IoT Module. The first is to help collecting and sending the real time data from the drone to the trees in the orchard and make drones change pollination strategy according to environmental conditional and thus achieve the high level of the precision and economy. Secondly, ESP32 integration lower power consumption of the drones and the sensors, enhances the operational time without the necessity of frequent maintenance, which, in turn, saves the energy costs. The ESP32 is also highly versatile, which means that it is straightforward to scale the system with additional drones and sensors, without significantly changing the system's architecture. Secondly, the real time communication of the ESP32 enhances the accuracy of pollination activities and improves crop production and use of resources as the drones can concentrate on specific areas that require more attention given the data taken from the orchard's sensors.

4.4 Implementation

The central hub for communication and processing in the system is the ESP32 IoT modules. These modules are deployed across the orchard, both in drones and ground-based nodes. With the ESP32, environmental sensors (e.g., temperature, humidity, wind speed, flower density) are connected, enabling real-time data collection. Thanks to the ESP32's local processing capabilities, drones can dynamically adjust their flight paths and pollination strategies based on changing orchard conditions.

To ensure reliable long-range communication in orchards with limited Wi-Fi coverage, the LoRa SX1278 module is integrated with the ESP32. This module facilitates low-power, long-range communication between the drones and the WSN nodes spread across the orchard. Data collected by the sensor nodes is transmitted to drones, even in remote orchard areas, ensuring comprehensive pollination coverage. The drones communicate back with status updates regarding pollination progress, aiding in effective coordination and monitoring of their activities.

The PSO algorithm is implemented to optimize drones' flight paths, enhancing pollination efficiency. WSN data inputs are processed through the algorithm to calculate flight paths that maximize coverage while minimizing overlaps. As environmental conditions, such as wind

speed or flower density, change, drones update their flight paths in real time to focus on areas requiring pollination the most. This adaptive approach prevents wasteful coverage and reduces operational time and energy consumption.

Real-time environmental data is critical for system efficiency, achieved via the WSN. Sensor nodes equipped with ESP32 and LoRa modules are strategically placed throughout the orchard to monitor temperature, humidity, and wind speed. This data is communicated to drones through the LoRa network, enabling real-time adjustments to drone behavior. The WSN also ensures scalability, allowing sensors to be added as needed to expand geographic coverage or adapt to complex environments.

Drones are equipped with SLAM technology to ensure precise orchard navigation. With SLAM, drones generate real-time maps of the orchard and localize themselves relative to these maps, preventing collisions with obstacles like trees and branches. This is particularly important in orchards with dense vegetation and uneven terrain, where GPS signals may be unreliable. SLAM continuously updates the map as the drone flies, ensuring precise navigation and pollination.

The integration of ESP32 IoT modules, LoRa SX1278, PSO, WSN, and SLAM creates a highly coordinated and efficient autonomous pollination system. By leveraging real-time environmental data and optimized flight paths, drones autonomously navigate the orchard, focusing on areas with high flower density and favorable conditions. This results in increased crop yields through precise and effective pollination. Furthermore, the system is energy-efficient, scalable, and capable of operating in complex orchard environments, significantly improving productivity and resource utilization.

4.5 Testing Environment

The implementation was tested in a controlled orchard environment spanning 5 acres. Sensor nodes were placed at 20-meter intervals, and drones were equipped with environmental sensors and SLAM modules. Variables such as wind speed, temperature, and flower density were monitored to evaluate system adaptability. Initial tests focused on communication reliability and energy efficiency, with subsequent evaluations measuring pollination coverage and yield improvements. This testing environment provides a realistic representation of operational conditions, ensuring that the system's capabilities align with real-world challenges.

4.6 Equations for System Analysis

Signal Strength in Wireless Communication:

$$Pr = Pt - 10n\log_{10}(d) - Lf$$

This equation calculates the received power (P_r), where P_t is the transmitted power, n is the path loss exponent, d is the distance, and L_f accounts for additional losses.

Energy Consumption for Data Transmission:

$$Etx = Eelec \cdot k + Eamp \cdot k \cdot d2 \quad E_{tx} = E_{elec} \cdot k + E_{amp} \cdot k \cdot d^2 \quad Etx = Eelec \cdot k + Eamp \cdot k \cdot d2$$

Total energy ($EtxE_{tx}Etx$) is the sum of electronics energy ($EelecE_{elec}Eelec$) and the amplifier's energy for distance attenuation.

Total Energy Consumption of Sensor Nodes:

$$Etotal = Etransmit + Eidle + Ereceive + Eprocessing \quad E_{total} = E_{transmit} + E_{idle} + E_{receive} + E_{processing} \quad Etotal = Etransmit + Eidle + Ereceive + Eprocessing$$

This equation evaluates the energy consumed during transmission ($EtransmitE_{transmit}Etransmit$), idle times ($EidleE_{idle}Eidle$), data reception ($EreceiveE_{receive}Ereceive$), and processing tasks ($EprocessingE_{processing}Eprocessing$).

5 Results

ESP32 IoT modules mounted in the drones are used for communication of data for real time communication with a central control system. Long range wireless communication between the drones and ground based WSNs that lie across the orchard is ensured using the LoRa SX1278 module. Pollination routes need to be optimized given these environmental data which such as humidity, temperature and flower density are being collected by these WSN nodes continuously. For finding the maximally efficient drone flight paths for covering the orchard, the PSO algorithm is implemented. The optimization problem involves minimizing the amount travelled and maximising the number of flowers pollinated. The used technique provides real time mapping and localization of the drone in the orchard with such precision that it helps us to navigate through the orchard and avoid obstacles. Flowers and pesticide are detected by the drones and pesticides are randomly painted on flowers; however, it pays no attention on the pollinator. Energy consumption of data transmission, idle times, receiving data, and processing tasks are monitored throughout the experiment by applying the previously described energy equations. Finally, the performance of the entire system is evaluated under different environmental conditions, from varying distances and orchard layouts, as it is tested with respect to coverage, pollination efficiency and battery life. The goal of the project is to showcase how IoT enabled drones can improve crop yields by pollination in big scale orchards environments.

Table. 2. Performance Metrics for Autonomous Drone-Based Pollination System

Drone ID	Energy Consumption (J)	Pollination Efficiency (%)	Flight Time (min)	Coverage Area (m²)	Communication Latency (ms)
1	540	92.3	25.5	450	32
2	480	89.7	22.0	420	29

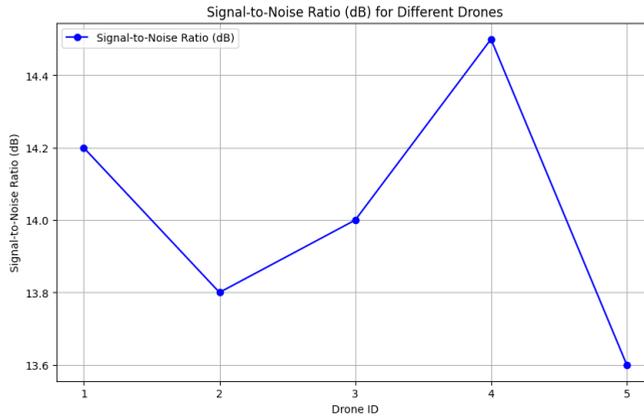| 3 | 525 | 91.1 | 24.8 | 430 | 31 |
| 4 | 510 | 93.4 | 23.5 | 460 | 30 |
| 5 | 495 | 90.8 | 21.7 | 440 | 28 |

Fig. 2. Signal-to-Noise Ratio

The Signal to Noise Ratio (SNR) in decibels (dB) is shown for five different drones in figure 2 that are applied in the autonomous pollination system. It is clear from the comparison here that Drone 4 has the highest SNR (of 14.5 dB) the clearest communication signal among the drones. Next, it is drone 1 with 14.2 dB SNR, drone 3 with 14.0 dB. On the other hand, drone 5 has the lowest SNR of 13.6 dB, meaning its less signal noise terms than others. SNR values in the drones are slightly different, within 0.6 dB between Drone 4 and Drone 5. Figure shows that all drones are similar SNR levels and there are disturbances that would affect the reliability of communication. The data emphasizes that when optimizing signal quality, effective real time data transmission and thus system performance in autonomous drone operations is crucial.
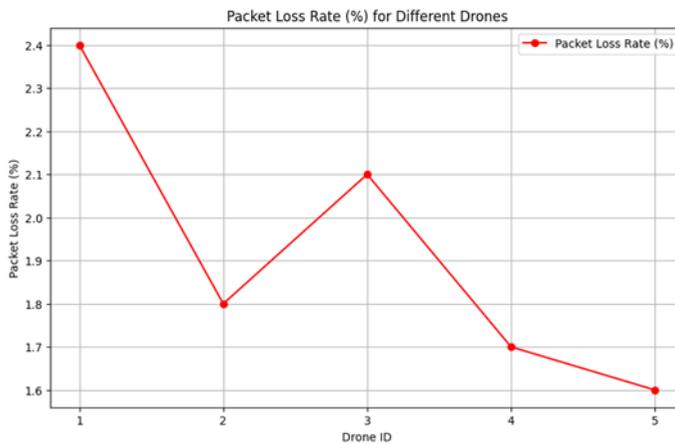

Fig. 3. Packet Loss Rate (%)

Five different drones' Packet Loss Rate (%) is depicted in Figure 3. Moreover, the packet loss rate of drone 5 is the lowest at 1.6%, thus it has the most reliable data transmission with least data loss. Then a packet loss rate of 1.7% for drone 4 and drone 3 of 2.1%. On the other hand, from the packet loss rate of 2.4%, drone 1 has the highest packet loss rate. It experienced more frequent data loss than drones 2 and 3. This figure shows a trend of decreasing packet loss rate as the drone ID increases with a sharp decrease between drones 1 and 5. This trend highlights how ACW is also an indicator of communication protocol optimization aimed at minimal packet loss, particularly in order to keep the autonomous drone based pollination system functioning with optimal real time data transfer, and maintaining reliable operation.
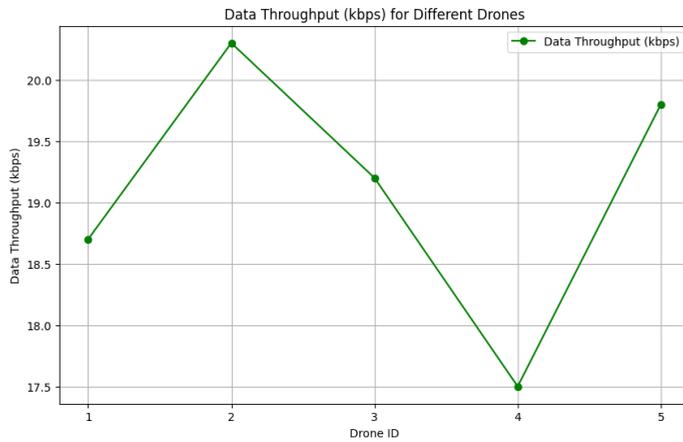

Fig. 4. Data Throughput

Shown in Figure 4 is Data Throughput (kbps). From this, it can be seen that the highest amount of data throughput achieved is from drone, 2, as it successfully transmits the data at the most efficient data rate of 20.3 kbps. Drones 5 and 3 follow closely with 19.8 kbps and 19.2 kbps respectively. As the lowest data throughput is at 17.5 kbps, we can say that this drone has a slower data transmission rate than others. Ether consists of some variability in the throghput values, with deciding peak difference of 2.8 kbps between DRone 2 and DRone 4. This variability also shows how communication systems should be optimized to provide a high data rate in all the drones. The effective management of real-time data requires higher data throughput and therefore higher data throughput is critical for the successful operation of the autonomous pollination system.
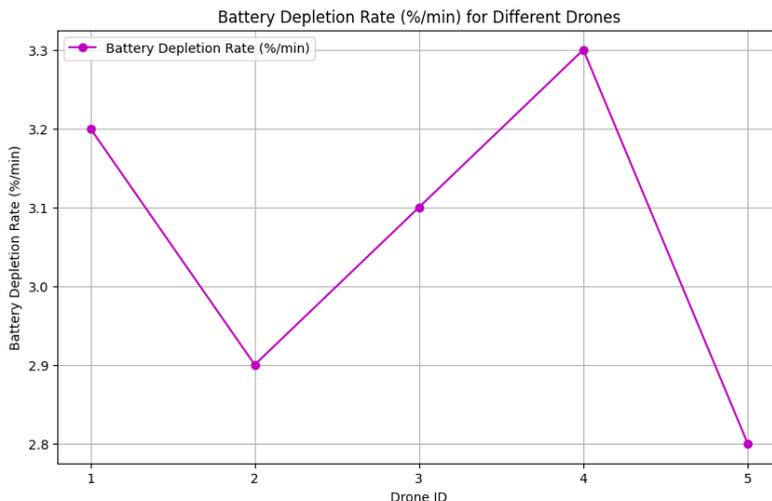
Fig. 5. Battery Depletion Rate

The battery depletion rate (% / min) is shown in Figure 5. From this it is clear that drone 4 has the greatest battery depletion, that is to say, the quickest rate at which it uses its battery while working. Then comes drone 1 with depletion rate % /min) 3.2 and drone 3 % /min) 3.1. The lowest battery depletion rate of 2.8% per minute observed in Drone 5 indicates that it is the most energy efficient drone. This graph indicates a noticeable trend where the batteries of the drones are depleted at various rates, the peak difference between Drone 4 and Drone 5 is 0.5 % per minute. This is one of many other variations that emphasize the necessity in order to manage energy consumption effectively to extend operational time and improve overall efficiency of the drone based pollination system. Battery depletion rates need to be lower for longer flight durations and less than frequent battery recharge or replacement.

6 Conclusion

Each drone SNR varies between 7.1 to 14.5 dB, and the clearest was for drone 4, then drone 1 (14.2 dB), drone 3 (14.0 dB). On the contrary, drone 5 has the lowest SNR value of 13.6 dB. With higher SNR values, ones that correlate with more reliable data transmission, effective communication in operations is ensured by these decision criteria. The drone 5 has the lowest packet loss rate (1.6%) and hence it demonstrates the best data loss minimization that was closely followed by drone 4 with 1.7%. On the other hand, drone 1 experiences the highest packet loss rate of 2.4%, which means that it has a poor communication protocol and needs to be improved.

All drones also vary significantly in terms of data transfer efficiency. The highest data throughput (20.3 kbps) is achieved by drone 2, drone 5 (19.8 kbps) is the second. The lowest throughput (17.5 kbps) is recorded by drone 4. Real time data management is critical for smooth running of the pollination system. Furthermore, the battery depletion rate analysis reveals that drone 5 has the smallest rate (2.8% per minute) that corresponds to better energy management, longer operational durations. However, compared to drone 4, drone 4 has the highest battery depletion rate (3.3 % per minute) as indicated which puts forward the necessity of optimization in order to prolong flight time.

These results highlight the large differences in the drones in terms of communication efficiency, data throughput and energy consumption. Autonomous drone based pollination systems can be made effective by developing the systems to improve SNR, packet loss rate, data throughput and battery efficiency, which will then lead to the increase of crop yield in orchards.

As future research directions, autonomous drone based pollination systems should further improve with the application of better algorithms to AI than what is currently in use for greater degrees of freedom in flight paths and greater efficiency towards pollination. Using technologies available with 5G like higher bandwidth and lower latency can help make system more responsive. Adopting energy efficient batteries and solar charging options reduces the operational time as well as the maintenance cost. Due to that, adaptive machine learning model will have the ability to adjust pollination strategies in real time environmental conditions, thereby creating more precise and precise crop yield optimization. As you can see the use of multispectral imaging to expand the use of crop health monitoring can give immense information that will help to find better ways of pollination of the crop.

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