Optimizing Communication Reliability in UAV Swarms: A Study on Antenna Configuration and Packet Loss Analysis

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***Abstract*—The use of Unmanned Aerial Vehicles (UAVs) in fields other than military has subsequently increased over the past years. A significant stride has been the development of protocols to avoid collisions between UAVs, enabling a seamless collaboration through swarm configurations. Despite technological advancements, packet losses during flight operations pose a challenge that deems attention. Losses can significantly hamper coordination within UAV swarms, underscoring the crucial importance of reliable communication. Another major shortcoming faced by quadcopter drones is their limited flight time. Drones used for our research, are limited to a flight time of 15 minutes. Thus, a reliable and low-latency communication with minimal packet loss is crucial for coordinated tasks. To address this challenge, our research aims on analyzing packet losses in swarm-based configurations employing drones equipped with ESP32 microcontrollers. Our focus extends to testing two different antennas to simulate real-world scenarios. Our research bridges the existing gap in understanding why these losses occur, specifically in swarm-based settings.**

***Index Terms*—UAV, Swarm-drone configuration, Packet Loss, ESP32, Antennas**

I. Introduction

Supported by rapid advancements in drone technologies and architecture, unmanned aerial vehicles (UAVs), such as battery-operated multicopter drones, have caught the eye of many researchers. The versatility of drones allows them to be used in multiple industries for various applications beyond just delivery scenarios, military applications, aerial photography, mapping construction sites [1], search and rescue operations, and security and surveillance [2]. The concept of swarm drones is operating and flying multiple UAVs operated from a single station. As per MarkNtel advisors, the swarm drone market is expected to grow at a 55% Compound Annual Growth Rate (CAGR) from 2022-2027 [3]. The market is expected to grow even more, primarily due to increased military applications and the defense sector. The main cause is security breaches at government sites and public places worldwide.

This paradigm shift from a single operating drone to a swarm presents new challenges and opportunities. Thus, the need to produce and maintain state of the art swarm technologies has gained importance, particularly in coordination among individual drones. This makes establishing a robust, reliable, and a low-latency communication network among the swarm members a must. Each drone in a swarm typically acts as a node within a dynamic network, exchanging sensor data, status updates, and commands with other drones in real time.

Despite not being a conventional tool for swarm setups, ESP32 could be an innovative solution given its versitility. It's integration of Wi-Fi and Bluetooth capabilities and use of ESP-NOW to facilitate a low-power low-latency communication between other modules has garnered attention in the design of the drone architecture developed by Cabuk et al. [4] for swarm drone configurations. Though ESP32 may not have been initially tailored for drone usage, the authors have successfully integrated it into a drone communication system and adapted a workaround that takes advantage of the ESP32s capabilities to meet drone-to-drone communication requirements effectively.

However, reliable transmission between drones presents its own inherent challenges. In dynamic and unpredictable environments, factors like multipath propagation, hardware limitations, Electromagnetic Interference (EMI) produced by the drone motors, the distance between drones, and signal interference can lead to packet losses which impact the overall performance and coordination of swarm-drone configurations. Loss of some sensor data can still be predicted; however, the loss of control packets can disrupt the planned swarm repositioning. This breakdown cascades further as the communication failures propagate through the swarm configuration, impacting other drones, which could lead to collisions or incorrect behavior and cause the failed drone to be a safety hazard.

Our research particularly focusses analysing losses in the architecture presented by [4] using ESP32 modules. The following bullet points highlight some unique contributions of our study.

- Investigating antenna oritentations and configurations to pick the best setup for minimal packet losses in a dynamic swarm drone setting taking into account different factors.
- Providing operational insights on the correlation between packet loss rate and drone states (grounded, mixed, and

airbourne).
- Exploring ESP32 integration on the drones to asses the the impact of drone dynamics on the communication reliability.

II. Related Works

It is crucial to understand and consider the current landscape of studies and developments in reception errors due to packet losses in drones. A study conducted by Ilnytska et al. [5] discusses the importance of understanding communication reliability in UAVs and the lack of quantitative information regarding packet loss in communication channels. It analyzes factors like network hub dependency, bandwidth impact, bit errors, travel time, and a chance of packet failure that could potentially decrease the Quality of Service (QoS) in communication channels.

Sai Venkat et al. [6] test the ESP-NOW protocol's efficacy within agro-industrial applications, highlighting its reliable connection with minimal packet loss. While the protocol performs well, especially when the drones are within range, challenges arise in challenging environmental situations requiring swarm repositioning, where controlling the packet losses becomes crucial to avoid the possibility of separation violation or collision in drones. Correspondingly, James et al. [7] study how deeply increased packet losses impact UAV path planning and repositioning algorithms, revealing a correlation between packet loss and the ability of an algorithm to maintain a safe inter-drone distance as the losses increase.

In this regard, Andre et al. [8] conclude that WiFi is a viable option. Nonetheless, the remote control of the ModalAI VOXL m500 used in our testing uses the same frequency, which could cause interference, resulting in an increase in the packet loss ratio, making it difficult to maintain a stable communication link. Study [9] also investigates the difficulty of wireless-link uncertainty affecting UAV swarm communications and system stability and presents a unique approach for optimizing swarm operations in the presence of network latency. The study gives useful insights for guaranteeing a stable UAV swarm configuration by examining the maximum acceptable delay.

Furthermore, several factors that influence a communication link in UAVs have been discussed and compared in [10]. Based on the telemetry parameters and Global Positioning System (GPS) information, they have also deduced that the link is influenced by ground reflection. Their study tests the performance using the droning tool [11] with the presence of interferences of devices operating in the 2.4GHz band. This study aligns closely with ours since it also takes into account the orientation of the antenna; however, high interference from the remote control prevented them from reaching a statistical difference.

Thus, there is still an opportunity for more in-depth research of current technologies to determine which is best suited for swarm UAV communications, considering special needs depending on the application.

A. Background on Wi-Fi Packet Loss

Wi-Fi packet losses can noticeably impact a network's performance and seamless data transfer between devices, making it essential to know the causes and effects of these losses. Understanding the cause of these losses is critical so that appropriate procedures can be followed to mitigate them. Silva [16] categorizes the losses into three types- Firstly, physical factors which include coexistence and interference due to other nearby devices and technologies, problems in the transmitting channel and fading. Secondly, collisions, i.e. when two devices in the same network transmit packets at the same time and lastly, buffer losses which is a result of network congestion which results in insufficient link rate and large buffers.

In addition to these types, EMI poses a significant challenge in Wi-Fi networks. This could be categorized as noise or radio frequency interference which is caused by natural or human-made sources. These devices emit electromagnetic waves that inturn interfere with the Wi-Fi networkds, including phones, video transmission devices and more [17]. Losses caused due to any of these reasons can significantly deteriorate the signal link and increase the Round Trip Time (RTT) in wireless networks.

TABLE I
DRONE SPECIFICATIONS

Drone Model	ModalAI VOXL m500
Flight Control	PX4 on VOXL Flight
Weight	1075g with battery
Propellers	10" (1045)
Battery and Weight	Gens Ace 3300mAh, 255g
R/C	Spektrum DSMX 2.4GHz RC Radio
Microcontroller	ESP32-WROOM-DA Module

III. Setup and Configuration

A. Assumptions

In studying the intricacies of swarm drone systems and packet loss analysis in the architecture developed by Cabuk et al. [4], several foundational assumptions helped us guide the course of our experimentation and research. The following assumptions served as a pillar upon which our tests and deductions are drafted within a dynamic drone environment.

1) Dynamic operational scenarios to test communication performance in varying conditions to observe losses.
2) Effect of multipath propagation [13] including effects of drone propellers, impacting inter-drone communication
3) Motors of a running drone produce EMIs which can potentially affect the signal link.
4) We hypothesize that the relative orientation of the transmitting and receiving antenna could potentially hamper the link strength [10]. A study by [14] also states this can affect communication reliability.
5) Increased distance between drones can weaken the communication link. We thus measure packet losses at different distances.

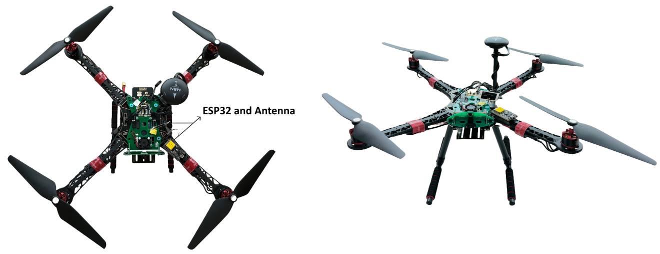

Fig. 1. ModalAI VOXL m500 drone used for test purposes

6) Signal interference from nearby device operating in the same frequency range can dispute communication link between the drones.

B. Test Hardware

In our work, we utilize ModalAI VOXL m500 (Figure 1), a powerful development drone which can be used for advanced autonomy development. This drone comes with a Snapdragon-based flight deck (VOXL) [15], a GPS module, and a variety of sensors onboard with a battery life of 15 minutes. The VOXL m500 combines Robot Operating System (ROS) and PixHawk4 (PX4) controller pilot, for obstacle avoidance using Visual Inertial Odometry (VIO) and GPS-denied indoor navigation. A tabular representation outlining the drone specifications can be seen in Table 1.

The drones have been integrated with ESP32 modules by the authors, acting as the external network interface. The modules are responsible for handling inter-drone communication and consequently offering ad-hoc networking capabilities utilizing the ESP-NOW protocol. The modules are programmed exclusively for the proposed drone architecture by Cabuk et al. [4].

Additionally, the ESP32 modules are incorporated with one of the two antennas in different testing scenarios- Particle 2.4GHz Band Antenna or the Molex Patch RF Antenna- to optimize reliability. The positioning of the module and the antennas can be seen in Figure 1. The role of antennas in our setup is crucial for ensuring a robust communication between the drones.

C. Test Software

Along with the other software components discussed in [4], the software controlling the external network interface, i.e., the ESP32, is where we focus on analyzing these packet losses. This is a program that runs on a loop on each of the ESP32s present on the drones in the configuration. This program acts as a gateway connecting all the drones within its range. Each drone in the architecture, housed with an ESP32 module, is connected to it via Wi-Fi. The module handles the communication between each drone through ESP-NOW protocol. Thus, the swarm is essentially a network of external interfaces individually connected to the carrier drone.

The code on the modules sets up a connection between them for the swarm drone applications. We configure Wi-Fi for dual mode operation (AP and STA) and use User Datagram Protocol (UDP) for data exchange. ESP-NOW is initialized for Peer-To-Peer (P2P) communication. By measuring the Received Signal Strength Indicator (RSSI) and setting other parameters for signal strength analysis, this framework enables testing the communication for reliability. External network communication is facilitated utilizing ESP-NOW for inter-node communication via Media Access Control (MAC) addresses.

D. Wireless Protocol

In this research and for the architecture developed by Cabuk et al. [4], ESP-NOW plays an integral role in facilitating communication between drones in swarm applications. It enables multiple ESP32 modules to communicate with each other without the use of Wi-Fi, making it very similar to the low power offered by 2.4GHz wireless connectivity. It is specially designed for P2P communication between ESP32 devices. The protocol operates at the Data Link Layer, bypassing the complexities of all the higher-layer protocols, creating an option for time-sensitive applications like drone swarm coordination. Some advantages of using the ESP-NOW protocol include- Coexistence with Wi-Fi and Bluetooth Low Energy (LE), fast pairing for one-to-may and many-to-many devices while also controlling them [9], utilizes lesser resources and is power efficient.

E. Test Scenarios

While the architecture [4] was successfully built, there was no means of keeping track of the success rate or the number of packets dropped by the external interface during transmission. To implement this, we modified the code that controls the external interface. We developed our test cases, keeping in account, the antenna orientation and positioning.

Our first set of tests were conducted indoors with variable distances and intermediate obstacles to emulate real-world scenarios. Notably, for these tests, the ESP32 modules we detached from the drones to establish baseline performance metrics. Though it is important to acknowledge propogation loss due to obstacles, this series of tests were conducted to observe the pattern for losses with each of the antennas.

Subsequently, the next set of tests was conducted with one of the ESP32 modoules connected to the computer and the other one housed on the drone. This was done with the drone motors running for one case and off for the next. This test was repeated at variable distances.

Our final set of tests was conducted with the ESP32 modules mounted on the drones and mimic real-world deployment. We began trasnmitting data packets on grounded drones with motors off. This was done to isolate any impact of aerial dynamics. Next, we transmitted packets with the motors on and subsequently, one drone was grounded while the other was air-bourne. Lastly, both drones were inflight emulating full operational deployment. Each test was repeaded twice, once with the antenna upward and once downward, for both antennas. This progression allows us to test our communication protocol amidst different drone activities. (Figure 2).

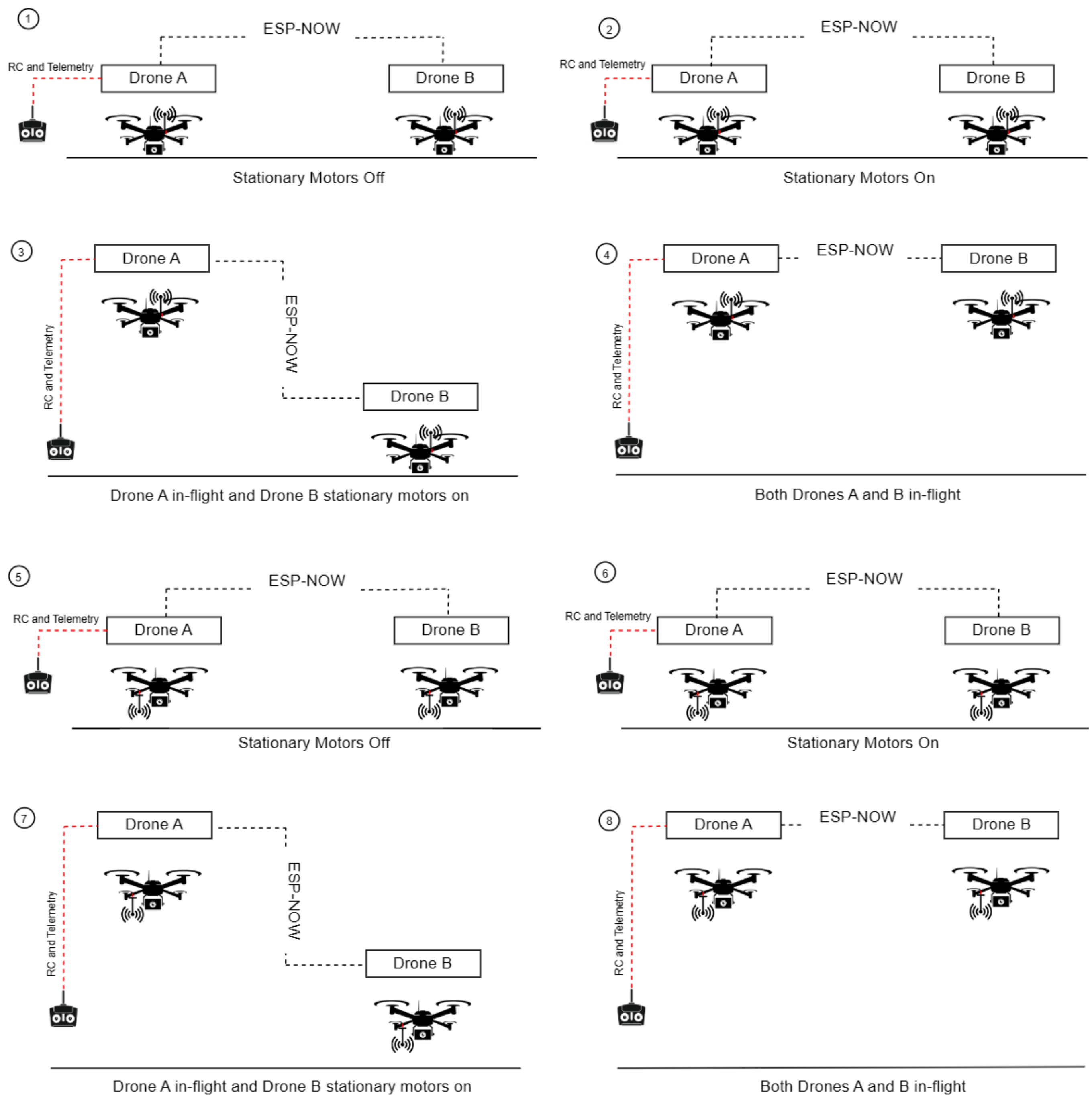

Fig. 2. In-Field Tests for Packet Loss Analysis

IV. Results and Discussion

In an indoor setting, the analysis revealed some significant insights into how different antennas under different orientation perform. After conducting the indoor set of tests we can clearly observe that the Molex Antenna shows a consistent performance and has relatively lower packet losses across larger distances and obstacles as compared to the Particle Antenna, particularly when the orientation of the antenna changes at increased distances, suggesting that the design of the antenna and frequency characteristics typically play an important role in mitigating losses. (Figure 3)

The observed differences in losses taking into account antenna types and motor states highlights the complexity of drone to drone communication dynamics in a swarm architecture. The findings of this study support the importance of mitigating losses and communication reliability. Since the drones in use support a limited battery life, this is particularly critical for quick coordinated tasks to ensure mission success.

In addition to this, the tests conducted with motors on and motors off highlight the influence of any EMI in drones.

A. Test Results

This section has a compilation of all the graphs obtained as a result of the tests we have conducted. The indoor tests conducted with the two antennas were to establish a basline performance metrics for success rate. The graph shown in Figure 3, compares the success rate for each of these antennas at different distances along with different antenna orientation.

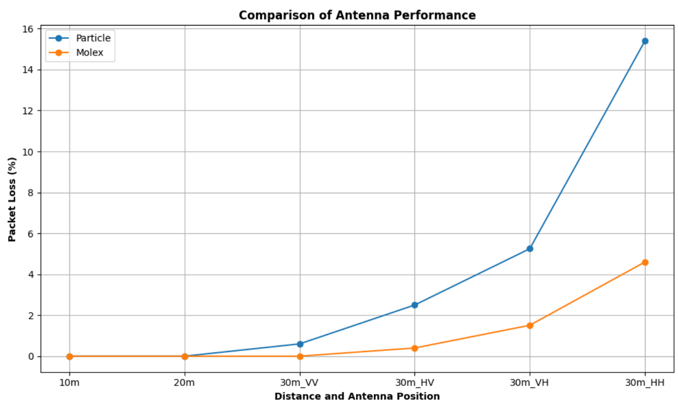

Fig. 3. Indoor Analysis without Drones

Case where one ESP32 was connected to the computer, and the other one connected to the drone (Figure 4), shows similar results to what we observed for the previous testing scenario across varying distances and different antenna orientations.

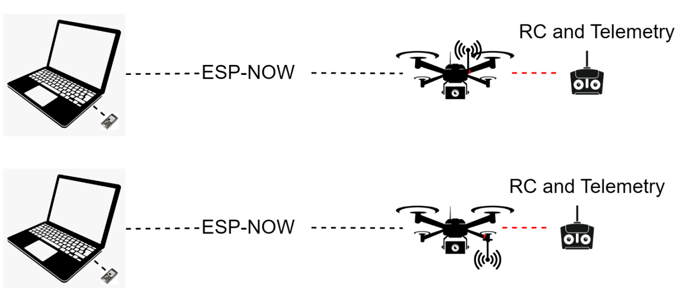

Fig. 4. Indoor Analysis with Drones

V. Conclusion and Future Works

As we conclude our investigation into swarm-drone communications, specifically in the context of the architecture discussed in [4] with the integration of ESP32 modules within a swarm, it becomes evident that we still face challenges and opportunities yet to be fully navigated in current literature.

This study dives deep into the challenge of tackling packet losses, particularly in the 2.4GHz frequency range, where the ESP32 based, ESP-NOW protocol operates. We identified potential sources of interference like neighbouring networks, drone hardware and various environmental factors, highlighting the need of a reliable, lwo-packet loss communication in swarm- UAV systems.

Furthermore, this study addresses criticla issues such as interferences by the drone propellers and motos, antenna optimization and orientation, and also simulating real-world scenarios to further improve communication reliability in the architecture. Through these tests, we gained insights into packet losses, signal degradation, and the performance of the architecture under various conditions.

Future works will focus on implementing advanced modulation techniques and dynamic change of modulation prioritizing critical packets, and DupCon implementation [10] could significantly advance in addressing packet losses in networked swarm.

Acknowledgment

This study was conducted under the research done at Drone and Bio-Sensor Lab with the Department of Electrical and Electronics Engineering at San Diego State University, San Diego, California, United States.

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