Performance Analysis of Network-Aware Micro-UAVs in Low-Altitude Applications

Disen Jia, Jonathan Kua and Xiao Liu
School of Information Technology
Deakin University, Geelong, Australia
{s223314816, jonathan.kua, xiao.liu}@deakin.edu.au

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***Abstract*—Reliable wireless connectivity is essential for the safe operation of Unmanned Aerial Vehicles (UAVs) in Low-Altitude Economy (LAE), particularly at low altitudes where network impairments can affect control accuracy and stability. In this paper, we present an empirical study on how network bandwidth, latency, and packet loss influence the performance of micro-UAVs, using an in-house Crazyflie-based experimental testbed. We conduct controlled experiments under varied network conditions to evaluate trajectory tracking and altitude control in vertical and square flight modes. Our results identify a critical bandwidth threshold, below which oscillations and control degradation emerge. We also observe increased waypoint dwell times and reduced responsiveness under constrained conditions. These findings provide practical insights for deploying UAVs in degraded communication environments and offer benchmark data to improve simulation fidelity. Our software and experimental datasets are publicly available to support reproducibility and further research in advancing network-aware UAV design for the growing LAE.**

***Index Terms*—Low-Altitude Economy, Micro-UAVs**

I. Introduction

The growing Low-Altitude Economy (LAE) relies heavily on the safe and reliable operation of Unmanned Aerial Vehicles (UAVs), which are increasingly used in infrastructure inspection, environmental monitoring, and urban logistics [1], [2]. These UAV systems depend on wireless communication for real-time control and telemetry, particularly in low-altitude environments where interference, latency, and packet loss are prevalent. Communication impairments in such conditions can lead to flight instability, control loss, or mission failure [3], [4]. These issues present significant barriers to large-scale UAV deployment and widespread adoption of LAE applications [5].

Recent efforts to standardize low-altitude traffic management systems have emphasized the need for resilient and predictable communication frameworks, while ensuring backward compatibility with existing Internet of Things (IoT) applications [6]. While prior studies have explored the impact of network quality on UAV systems, they often focus on isolated parameters or rely heavily on simulation-based validation [7]. Hardware-in-the-loop experimentation remains limited, particularly for micro-UAVs, which operate with tighter control loops and more constrained resources [8], [9].

Despite growing interest in UAV communication performance, several critical gaps remain in the current body of research [10], [11]. First, there is a lack of systematic analysis quantifying how specific network parameters, such as bandwidth limitations, latency, and packet loss, affect flight performance. Second, the behavioral patterns and stability thresholds of micro-UAVs under degraded network conditions are not well understood. Third, there is a shortage of empirical benchmark data that can support the calibration of simulation platforms for realistic UAV control scenarios. These limitations hinder both the reliability of deployed UAV systems and the accuracy of simulation-based studies.

In this paper, we systematically evaluate how key network parameters affect the performance of a micro-UAV system. Using the Crazyflie 2.1[1] platform to build our testbed, we emulate degraded network environments and analyze UAV behavior in vertical and square trajectory flight modes. Our focus is on control responsiveness, tracking precision, and stability under constrained communication. Our software, datasets and experimental results are made publicly available on GitHub[2].

In summary, we make the following key contributions:

- Design and implement a controlled experimental framework to inject precise network impairments into a micro-UAV control loop in real time.
- Identify a sharp control degradation bandwidth threshold, below which the micro-UAVs exhibit oscillation and loses trajectory tracking accuracy.
- Provide quantitative analysis of waypoint dwell times and control performance under a wide range of network conditions, including varying bandwidth, latency, and packet loss.
- Generate benchmark data that can be used to calibrate network-aware UAV simulators, helping bridge the gap between simulation and physical deployment.

The remainder of this paper is structured as follows. Section II reviews related work on micro-UAV systems and communication constraints in low-altitude environments. Section III describes the experimental testbed, network impairment injection framework, and flight modes used for evaluation. Section IV presents the results and analysis of UAV performance under varying bandwidth, latency, and packet loss conditions. Finally, Section V concludes the paper and outlines directions for future work.

[1] https://www.bitcraze.io/products/old-products/crazyflie-2-1/
[2] https://github.com/JudsonJia/UAV_Network_Test

II. Background and Related Work

In this section, we present relevant background on micro-UAV applications, communication technologies, and simulation practices, and review existing literature to identify key research gaps addressed in this work.

A. Micro-UAV Applications and Control Challenges

Micro-UAV technology has advanced significantly in recent years, particularly for indoor and confined-space applications. Samavedula et al. [12] proposed a cost-effective indoor mapping system based on nano drones, using simple distance sensors in place of expensive LiDAR, highlighting the potential of micro-UAVs in complex environments. Similarly, Neumann et al. [13] deployed Crazyflie 2.0 swarms for industrial monitoring and identified power and payload limitations as key technical constraints. Pambudi et al. [14] developed a nano quadcopter-based heat source detection system, further demonstrating the unique advantages of micro-UAVs in specialized environmental sensing tasks. Yen et al. [15] successfully implemented an indoor multi-UAV sound source tracking system, demonstrating the feasibility of complex coordination tasks using Crazyflie platforms with custom microphone arrays.

From a control perspective, Comandini et al. [16] introduced a policy gradient-based online reinforcement learning strategy that improves quadcopter flight performance in uncertain environments by dynamically adjusting control parameters. Vong et al. [17] showed that micro-UAVs in confined spaces experience significant aerodynamic disturbances and require specialized control schemes to mitigate effects such as the "tunnel effect."

B. UAV Communication and Networking Protocols

Research on UAV communication technologies spans multiple technical challenges. In the context of swarm coordination, Li et al. [18] modeled UAV swarm mobility using a D-Gauss-Markov framework and analyzed the reliability of self-organizing networks under varying formation geometries. Their work provides a theoretical foundation for evaluating Ad Hoc communication in UAV swarms.

In routing protocol optimization, Meng et al. [19] proposed FX-AODV, an improved version of the classic AODV protocol. It incorporates multiple routing metrics, including signal strength, congestion level, node energy, and hop count. Their results show that FX-AODV, enhanced via an ant colony optimization algorithm, outperforms standard AODV in terms of delivery rate, delay, and node longevity.

Arrabal et al. [7] demonstrated experimentally that concurrent Wi-Fi traffic can increase UAV command delay variability by up to 300%, severely affecting system stability. However, most prior studies focus on isolated parameters and do not conduct multi-dimensional, systematic evaluations of communication effects on control.

C. Effect of Communication Delay on UAV Control

The impact of communication delay on UAV control systems is inherently multi-dimensional. Fagundes-Junior et al. [20] found that for the AR.Drone 2.0 platform, noticeable performance degradation begins beyond 100 ms of delay. However, their study focused on UAVs reliant on external computation, differing fundamentally from the architecture of autonomous micro-UAVs. Their simulations showed that with appropriate control gains, the system can tolerate delays up to 1.2 seconds, but the platform-specific nature of this result limits its generalizability across different UAV designs.

D. Simulation and Experimental Platforms

The work in [8] surveyed 1,738 UAV-related papers and noted a growing trend toward simulation-based validation over hardware experimentation, driven by efficiency and regulatory considerations. While this shift enhances accessibility, it also highlights the scarcity of real-world test data, particularly for modeling micro-UAV dynamics under network degradation.

A comprehensive review of UAV network simulation tools is performed in [21], which classifies them into UAV simulators, network simulators, channel simulators, and co-simulation platforms. They also compiled a set of open-source tools. However, most simulators rely on idealized models that do not capture platform-specific sensitivity to network conditions. For example, micro-UAVs such as Crazyflie use lightweight control stacks that respond differently to network impairments compared to larger systems [22].

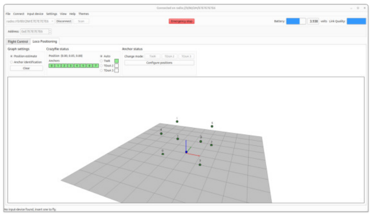
E. Research Gaps and Motivation

A review of the literature reveals several critical gaps. First, there is a lack of systematic, quantitative analysis of how key network parameters (bandwidth, latency, and packet loss) jointly affect micro-UAV flight performance. Second, existing research provides limited insight into the behavioral thresholds of micro-UAVs under degraded network conditions. Third, most UAV simulation platforms lack empirically grounded calibration data, limiting their accuracy for modeling real-world low-latency control systems.

To address these gaps, this paper presents a comprehensive experimental evaluation of the Crazyflie micro-UAV under varying network conditions. Through controlled emulation of bandwidth, latency, and packet loss, we analyze the effects of communication constraints on flight stability and control precision. The results provide both practical design guidance for network-aware micro-UAV operation in the Low-Altitude Economy (LAE) and empirical benchmarks to enhance the fidelity of UAV simulation platforms.

III. Experimental Methodology

In this section, we describe the experimental platform, network emulation framework, control software, and error analysis methods used to evaluate the impact of network conditions on micro-UAV behavior. Figure 1 shows the complete experimental environment setup, including the 3D visualization interface of the Loco positioning system and the actual physical test environment (3m × 3m × 1.7m).



(a) The Loco positioning system interface shows the spatial distribution of 8 UWB anchor points and the real-time location of the Crazyflie drone.

(b) The physical experiment setup showing the Crazyflie 2.1 UAV positioned at the center of a red flight zone.

Fig. 1: Experimental setup: (a) 8 UWB anchor positioning system showing real-time Crazyflie location, and (b) physical test environment with UAV in flight zone.

A. Testbed Configuration

The experimental platform is based on the Crazyflie 2.1, a 27 g micro-quadcopter equipped with an STM32F405 microcontroller, nRF51822 radio, BMI088 IMU, BMP388 pressure sensor, and DWM1000 UWB module for positioning [23]. A Crazyradio PA USB dongle (2.4 GHz, 20 dBm) [24] provides downlink control. Positioning is achieved using an 8-anchor Bitcraze Loco Positioning System with a reported accuracy of ±10 cm within a 10 m range [25]. The ground control station runs on a Linux-based system with an Intel i7 processor, 16 GB RAM, and USB 3.0 interfaces.

B. Software Implementation

1) RF Network Simulation: We implemented a unified network impairment injector to emulate constrained bandwidth (via time-window throttling), latency (via priority queuing), and packet loss (via probabilistic dropping). These constraints are applied directly to the position setpoint messages transmitted from the control station to the drone.

2) Battery Diagnostics: To ensure safety and stable flight conditions, a 3.8 V battery threshold was implemented with real-time voltage monitoring using the Crazyflie's LogConfig callback mechanism.

3) Position Control and Monitoring: The control loop operates at 100 Hz with separate tolerances for different flight phases. During transit, a tolerance of 0.15 m ensures smooth trajectory tracking, while during waypoint verification, a tighter 0.08 m threshold is used to confirm stability. Stability is defined as maintaining position within the threshold for either 20 or 40 consecutive samples, depending on the waypoint distance. For movement-based thresholds, distances >0.25m require 40 stable readings, ≤0.25m require 20 readings.A 10-second timeout prevents indefinite waiting. UAV position is logged at 20 Hz with thread-safe buffering for post-analysis.

4) Error Calculation and Analysis: The flight phase classification, waypoint phase error and stability conditions are defined below.

a) Flight Phase Classification: The waypoint and transit flight phases are classified as follows.

$$\text{Phase} = \begin{cases} \text{waypoint}, & \text{if } |P - W| < 0.15 \text{ m} \\ \text{transit}, & \text{otherwise} \end{cases} \quad (1)$$

b) Waypoint Phase Error: Direct Euclidean distance: $E_{waypoint} = |P - W| = \sqrt{(x - x_w)^2 + (y - y_w)^2 + (z - z_w)^2}$

Component errors: $E_{XY} = \sqrt{(x - x_w)^2 + (y - y_w)^2}$, $E_Z = |z - z_w|$

Stability condition: $|x - x_w|, |y - y_w|, |z - z_w| < 0.08$m

c) Transit Phase Error (TPE): The TPE for vertical and square trajectories are calculated as follows.

- *Vertical Trajectory*: Time-interpolated height error using normalized progress $t = \frac{t_{current} - t_{start}}{t_{end} - t_{start}}$, expected height $Z_{expected} = Z_{start} + t(Z_{end} - Z_{start})$, and vertical error $E_Z = |Z_{actual} - Z_{expected}|$.
- *Square Trajectory*: Path projection error using parameter $t = \frac{(P-A)\cdot(B-A)}{|B-A|^2}$ (clamped 0-1), projected point $P_{proj} = A + t(B - A)$, and 3D error $E_{3D} = |P - P_{proj}|$.

d) Statistical Robustness: Z-score outlier detection removes values with $|Z_i| = |\frac{E_i - \mu}{\sigma}| > 3.0$. 95% confidence intervals: $CI_{95\%} = \frac{1.96 \times \sigma}{\sqrt{n}}$.

C. Experimental Network Conditions

Baseline bandwidth testing (motors disarmed for safety) confirmed that Crazyflie requires 12.8 kbps for reliable 100 Hz command streaming. We then conducted controlled flights under a matrix of network conditions:

- Bandwidth: 10.0, 5.0, 1.28, 0.5, 0.25, 0.2, 0.225 kbps
- Latency: 0, 50, 100, 200, 500 ms
- Packet Loss: 0%, 5%, 10%, 20%, 30%, 97%, 98%

Each configuration was repeated multiple times to ensure reproducibility and statistical significance. Flight dynamics are controlled through standardized parameters, 3.8V battery thresholds, and automated scripting, isolating network impacts from velocity variations.

TABLE I: Crazyflie 2.1 Baseline Bandwidth Test Results

Frequency (Hz)	Success Rate (%)	Command Time (ms)	Bandwidth (kbps)
10	100.0	0.047	1.28
20	100.0	0.017	2.56
50	100.0	0.016	6.40
100	100.0	0.014	12.80
200	100.0	0.013	25.60

D. Flight Mode Characteristics

Two representative flight patterns were used:

- *Vertical Flight:* A 5-point altitude sequence (0.3 m → 0.6 m → 0.9 m → 0.6 m → 0.3 m) to assess hover precision and stability under time-interpolated reference tracking.

- *Square Trajectory:* A closed-loop trajectory with 1.0 m side length, centered on the origin, to evaluate trajectory tracking and corner behavior.

These modes represent common navigation patterns in LAE applications, enabling differentiated analysis of point-based versus continuous path-following tasks.

IV. Performance Evaluation and Analysis

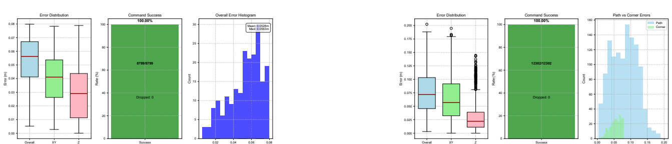
This section presents our experimental results and analysis. We conducted network-aware experiments on two major sets of flight paths/trajectories.

For *vertical flight*, the analysis focuses on the waypoint phase to evaluate hovering precision at discrete altitude setpoints (0.3 m, 0.6 m, and 0.9 m). When the UAV begins to oscillate beyond the stability threshold, the mean position error becomes less meaningful. However, a noticeable increase in XY-plane error distribution serves as a strong indicator of sustained oscillatory behavior at a fixed altitude.

The *square trajectory* analysis considers the full flight path, including both transit and waypoint phases, to assess path-following accuracy and cornering behavior. From baseline conditions down to 0.25 kbps, the number of detected corner points increases steadily, reflecting consistent trajectory tracking. Below 0.25 kbps, however, the UAV fails to register corners reliably due to control instability. As a result, corner points decrease sharply and are replaced by path-segment points, reflecting oscillations around setpoints rather than successful corner execution.

A. Baseline Performance

As a benchmark, we run experiments where the micro-UAVs are flying under optimal network conditions, i.e., high bandwidth, minimal latency, 0% induced packet loss. Fig. 2 presents the baseline performance for both flight trajectories.



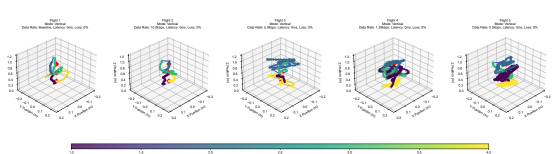
(a) Vertical flight (b) Square flight

Fig. 2: Baseline performance under optimal conditions.

Critical bandwidth threshold discovered between 0.225-0.25kbps, as illustrated in Fig. 3 and Fig. 4. Under this threshold condition, the flight trajectory of the unmanned aerial vehicle showed severe drift and oscillation phenomena.

B. Flight Trajectories

Figs. 3 and 4 illustrate the flight trajectory performance under various network conditions for vertical and square trajectories, respectively.



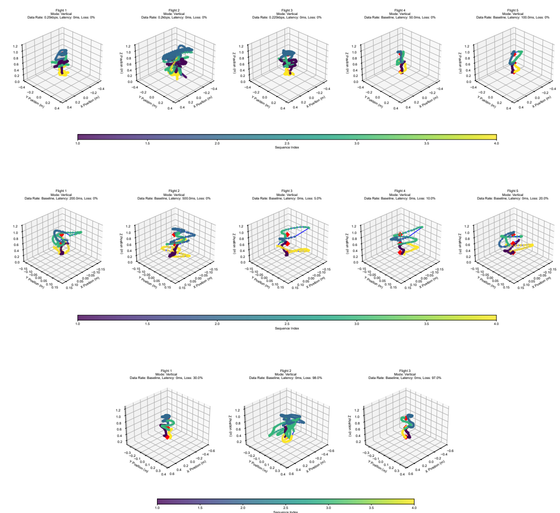


Fig. 3: Vertical trajectories under various network conditions.

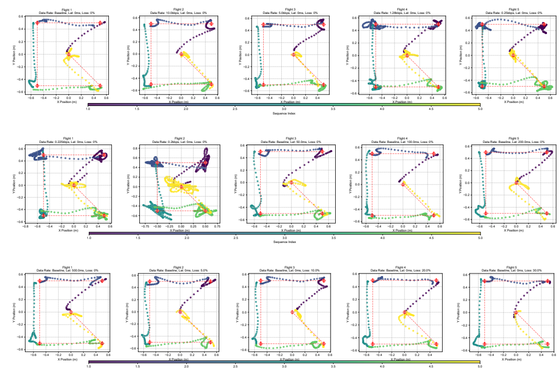


Fig. 4: Square trajectories under various network conditions.

C. Bandwidth Impact Analysis

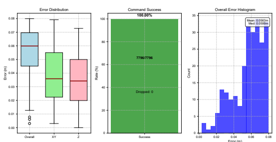
Critical bandwidth threshold discovered between 0.225-0.25kbps, as illustrated in Fig. 5 and Fig. 6. Under this threshold condition, the flight trajectory of the micro-UAV showed severe drift and oscillation phenomena. We present our key observations and findings below.

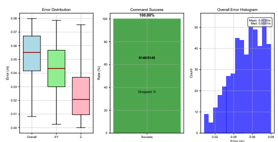
a) Critical Bandwidth Threshold: From 10.0 kbps down to 0.25 kbps, the UAV maintained stable flight without control loss, as illustrated in Fig. 5 and Fig. 6. However, reducing bandwidth progressively increased waypoint dwell time, giving the appearance of improved position accuracy due to denser hover-phase data. At 0.2 kbps, uncontrollable oscillations were observed. Using binary search, persistent instability was confirmed at 0.225 kbps (see Fig. 3 and Fig. 4). We identify the critical bandwidth threshold for stable Crazyflie flight as between 0.225 kbps and 0.25 kbps.

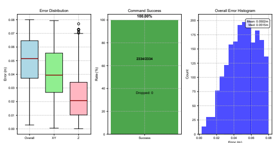
b) Bandwidth Constraints Mechanism: Bandwidth directly limits the frequency at which control commands can be transmitted. At 100 Hz and 128 bits per command, the baseline requires 12.8 kbps. At 0.25 kbps, this drops to approximately 1.95 commands per second. Below 0.225 kbps, the effective rate falls under 1.76 commands per second, which is insufficient to maintain control authority.

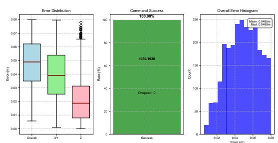
c) Waypoint Dwell Time Phenomenon: Lower bandwidth increases waypoint dwell time due to the stability verification logic. At baseline (100 commands per second), rapid stability confirmation allows quick waypoint transitions. At 0.25 kbps (1.95 commands per second), each verification cycle takes around 0.5 seconds, requiring 10–20 seconds to accumulate sufficient stable readings before advancing.

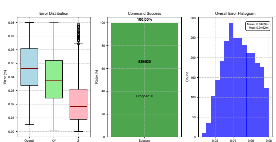
d) Control System Limitations: The sharp transition between 0.225 kbps and 0.25 kbps reflects a fundamental limitation of the Crazyflie architecture. Its internal 500 Hz attitude controller compensates for reduced external command frequency down to $\sim$ 1.8 Hz. Below this threshold, the command gaps become too wide for smooth control, resulting in overcorrections and sustained oscillations.


(a) 10kbps


(b) 5kbps


(c) 1.28kbps


(d) 0.5kbps


(e) 0.25kbps

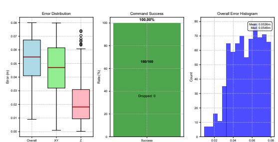
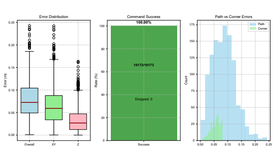
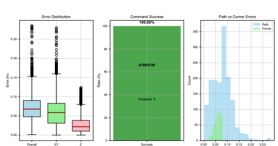
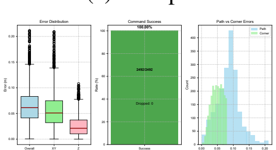
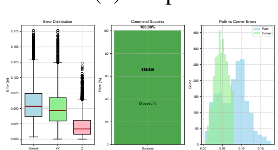

(f) 0.225kbps

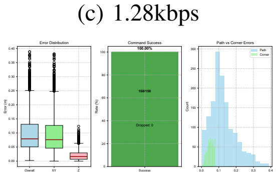
Fig. 5: Vertical flight performance under bandwidth constraints.


(a) 10kbps


(b) 5kbps


(c) 1.28kbps


(d) 0.25kbps


(e) 0.2kbps

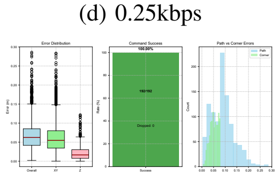
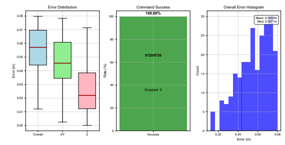
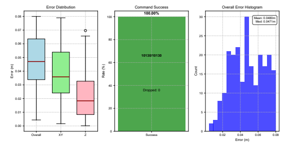

(f) 0.225kbps

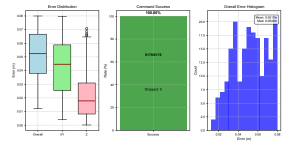
Fig. 6: Square flight performance under bandwidth constraints.

D. Latency Tolerance Evaluation

The impact of latency on UAV performance is demonstrated in Fig. 7 and Fig. 8.


(a) 50ms


(b) 100ms


(c) 200ms

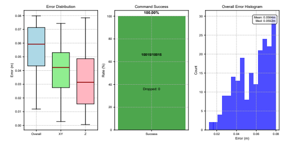
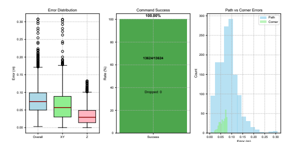
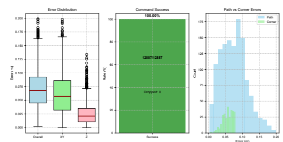
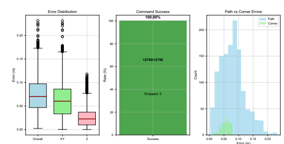

(d) 500ms

Fig. 7: Vertical flight performance under latency constraints.


(a) 50ms


(b) 100ms


(c) 200ms

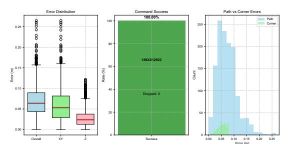

(d) 500ms

Fig. 8: Square flight performance under latency constraints.

a) Latency Impact Characteristics: Latencies between 50 ms and 500 ms had negligible impact on flight stability or trajectory tracking, as shown in Fig. 7, Fig. 8, Fig. 3, and Fig. 4. Note that this refers to total system latency (command set delay), not inter-command intervals. For timing-critical behavior due to sparse commands, refer to the bandwidth analysis, which defines equivalent delay thresholds.

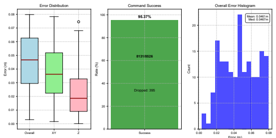
b) Buffering and Control Loop Behaviors: Crazyflie's onboard 500 Hz attitude controller ensures stability during communication delays by relying on internal sensor feedback from the gyroscope, accelerometer, and barometer, even when awaiting new position commands.

c) Command Queuing Effects: System-wide latency introduces a time offset between control intent and UAV response, rather than degrading stability. During delay periods, the drone continues executing previous commands while new ones queue in sequence, resulting in delayed trajectory transitions rather than command failure.

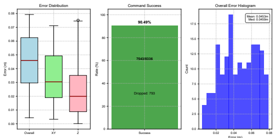
Latency up to 500 ms did not result in a severe performance degradation. Bandwidth reduction to 0.225 kbps caused immediate instability, as shown in Figs. 3 and 4. The inter-command delay threshold can be derived from the bandwidth limit: a minimum rate of 1.8 commands per second corresponds to a maximum inter-command interval of $\sim$ 556 ms.

E. Packet Loss Resilience Evaluation

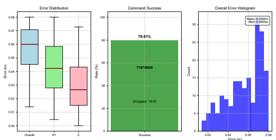
Figs. 9 and 10 presents results on the impact of packet loss on the performance of vertical and square flight trajectories, respectively.



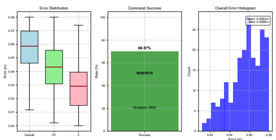
(a) 5% loss



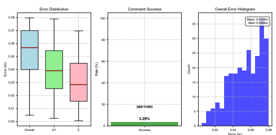
(b) 10% loss



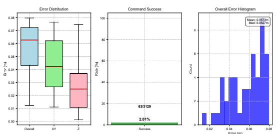
(c) 20% loss



(d) 30% loss

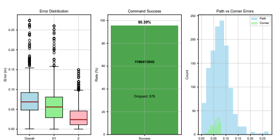


(e) 97% loss

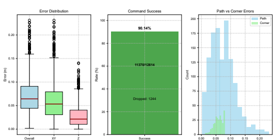


(f) 98% loss

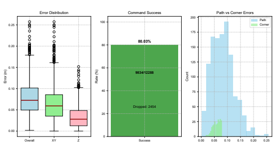
Fig. 9: Vertical flight under packet loss conditions.



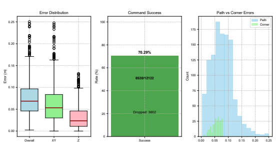
(a) 5% loss



(b) 10% loss



(c) 20% loss



(d) 30% loss

Fig. 10: Square flight under packet loss conditions.

a) Low-to-Medium Packet Loss (5%–30%): Packet loss in the 5%–30% range had minimal impact on flight performance. This is attributed to two main factors: (1) the 100 Hz command transmission rate provides substantial redundancy—at 30% loss, 70 commands per second still reach the UAV, which is more than sufficient for real-time control (see Fig. 10); and (2) the Crazyflie's onboard sensor fusion maintains accurate state estimation during intermittent external command loss.

b) Extreme Packet Loss Validation: To validate the bandwidth threshold, we calculated the equivalent packet loss at 0.225 kbps. At baseline, each command is 128 bits (16 bytes), so 12.8 kbps supports 100 commands per second. At 0.225 kbps, this drops to 1.76 commands per second, which is equivalent to 98.24% packet loss:

$$\text{Equivalent Packet Loss} = \left(1 - \frac{1.76}{100}\right) \times 100\% = 98.24\%$$

Experimental results on vertical flight confirmed this estimate: at 97% packet loss, the UAV maintained relatively normal flight behavior; at 98%, the system experienced irreversible oscillations (see Fig. 3), consistent with the observed bandwidth threshold.

c) Behavioral Differences: Bandwidth vs. Packet Loss: Although 98.24% packet loss and 0.225 kbps bandwidth are mathematically equivalent in command delivery rate, their operational impact differs significantly due to timing behavior.

- *Bandwidth constraints:* Deterministic command intervals of ~ 0.57 s allow the UAV to anticipate command arrival, leading to extended waypoint dwell times and oscillations until the 10-second timeout is reached.
- *High packet loss (98%):* Random distribution of retained packets at 100 Hz may create clustered arrivals, enabling rapid verification and potentially triggering the drone's protection mechanism (e.g., automatic landing) before test completion.

These results reinforce the finding that *command arrival timing patterns are more critical than average command rate* for maintaining micro-UAV control stability.

V. Conclusions and Future Work

In this paper, we presented an empirical evaluation of how bandwidth, latency, and packet loss affect micro-UAV performance, using the Crazyflie platform as a representative testbed for LAE applications. We identified a platform-specific bandwidth threshold between 0.225 and 0.25 kbps, below which control stability sharply degrades. In contrast, Crazyflie tolerated delays up to 500 ms and packet loss up to 97% without critical instability, highlighting the influence of onboard control architecture.

A key insight is that command arrival timing patterns are more critical than average rate. Although mathematically similar, bandwidth limitations and high packet loss produce different behaviors due to their temporal characteristics. We also observed the *"waypoint dwell time phenomenon"*, where low bandwidth skews error measurements due to extended hovering during verification. Our results emphasize that simulation platforms must model platform-specific control logic and command timing behavior, not just network throughput. While this study focuses on a single platform and indoor conditions, future work will generalize findings across UAV types, explore dynamic network environments, and develop adaptive, architecture-aware control strategies.

Building on these results, future work will focus on validating the observed performance thresholds across diverse micro-UAV platforms and communication stacks. We also aim to investigate dynamic network conditions, such as mobility-induced channel variation and bursty loss patterns. Another direction involves developing architecture-aware control systems that adapt behavior in real time based on link quality metrics. Finally, we plan to incorporate these findings into simulation frameworks to support realistic, platform-specific modeling of networked UAV operations.

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