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**An In-Depth Research on Drone Communication Systems**

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# Introduction

This document has been created to consolidate the extensive research and discussions surrounding the design and implementation of a drone communication system. With rapid technological advancements and an ever‐growing demand for efficient unmanned aerial systems, our project investigates various communication protocols, hardware configurations, and antenna solutions for achieving robust data transmission between the drone and its ground controller.

The primary objectives of this document are to:

* Provide an overview of the different research questions and technical challenges we have addressed.
* Present an in-depth analysis of communication options, including statistical performance, interference issues, and practical tradeoffs.
* Summarize the key conclusions derived from our research efforts.
* Outline the decisive choices made regarding the system’s design based on rigorous comparisons.

In doing so, the document will highlight the pros and cons of each system, supported by tables that compare different communication modules (such as ESP32 Wi-Fi, LoRa, NRF24L01+, and SX1278-based systems) and the fitting criteria for our drone project.

# 1. Research Questions

The leading question to our smaller research questions is: *“What is the most reliable, interference-resilient, and efficient communication architecture (in terms of protocol, frequency band, antenna choice, and system design) for real-time drone telemetry and control in both open and interference-prone environments?”* This has led us to explore a wide variety of technical questions. The following research questions represent the core challenges we have addressed:

## 1.1 Communication Protocols and Frequency Bands

* **What are the benefits and limitations of using the ESP32’s built-in 2.4 GHz Wi-Fi module versus other RF modules (e.g., SX1278 for LoRa)?**
* **Can raw 802.11 frames be effectively utilized for low-level communication between drones and ground stations?**
* **What is the feasibility of designing custom libraries to “spray” data over the air using raw Wi-Fi frames?**

## 1.2 Antenna Design and Performance

* **What are the differences between integrated PCB antennas, whip/monopole antennas, helical antennas, and chip antennas for LoRa communication?**
* **How does the performance of a simple copper coil antenna on the drone compare with that of a directional antenna on the controller?**
* **What are the tradeoffs in terms of efficiency, radiation pattern, and tuning requirements for each antenna type?**

## 1.3 System Integration and Interference

* **How do various environmental factors and interference from other 2.4 GHz devices impact system performance?**
* **What design measures (e.g., error checking, retransmission protocols, encryption) can be implemented to mitigate interference and packet loss?**
* **What are the real-world range expectations for each system configuration, and how do antenna choices influence these distances?**

## 1.4 Protocol Robustness and Data Handling

* **What are the key elements of a robust communication protocol for drone telemetry and control?**
* **How can Quality of Service (QoS) data frames be utilized to prioritize critical data (such as flight control commands) over non-critical telemetry?**
* **Is it necessary to develop custom firmware for the ESP32, or can existing libraries (ESP-NOW, UDP, raw Wi-Fi) be adapted to our needs?**

These questions have shaped our research direction, guiding us through experimental setups, prototype development, and system performance evaluations.

# 2. In-Depth Analysis

In this section, we delve into detailed research findings regarding communication protocols, interference, antenna performance, and system integration. Our analysis covers technical aspects, performance statistics, and the pros and cons of each system configuration.

## 2.1 Communication Options and Protocols

### 2.1.1 ESP32 Wi-Fi (2.4 GHz)

* **Overview:**  
  The ESP32 Wi-Fi module is a widely used solution due to its ease of use, robust community support, and versatility.
* **Advantages:**
  + Easy integration with existing libraries.
  + Supports raw frame injection via the esp\_wifi\_80211\_tx() function.
  + Capable of both traditional Wi-Fi networking and custom low-level communications.
* **Disadvantages:**
  + Operates in a congested 2.4 GHz band, prone to interference.
  + Limited range when using built-in PCB antennas.
* **Statistical Insights:**
  + Typical line-of-sight range is between 100–300 m with an external antenna.
  + Indoors, range drops to approximately 20–50 m.

### 2.1.2 SX1278 for LoRa

* **Overview:**  
  The SX1278 module, based on LoRa technology, offers long-range communication with low data rates, making it ideal for telemetry in challenging environments.
* **Advantages:**
  + Excellent range (up to 10 km in open areas).
  + Low power consumption.
  + Operates on less congested frequency bands (433, 868, or 915 MHz).
* **Disadvantages:**
  + Low data throughput (not suited for real-time video).
  + Requires precise antenna tuning and matching.
* **Statistical Insights:**
  + Effective range can reach several kilometers with optimal conditions.
  + Data rates vary from 0.3 kbps to 37.5 kbps.

### 2.1.3 NRF24L01+ Modules

* **Overview:**  
  The NRF24L01+ is a cost-effective module that offers low latency and moderate range, also operating in the 2.4 GHz band.
* **Advantages:**
  + Low latency ideal for control signals.
  + Relatively low cost.
* **Disadvantages:**
  + Also subject to 2.4 GHz interference.
  + Range is moderate, often around 1–2 km with PA+LNA variants.
* **Statistical Insights:**
  + Latency is typically under 5 ms.
  + The maximum data rate is around 2 Mbps, but practical throughput is lower.

### 2.1.4 ESP-NOW

* **Overview:**  
  ESP-NOW is a proprietary protocol by Espressif that allows for direct, low-latency communication without the overhead of Wi-Fi networking.
* **Advantages:**
  + Very low latency (under 5 ms).
  + No need for a Wi-Fi access point.
* **Disadvantages:**
  + Limited packet size (approximately 250 bytes per packet).
  + Limited to ESP32/ESP8266 ecosystems.
* **Statistical Insights:**
  + Optimized for small, quick bursts of data, suitable for real-time telemetry.

**Comparison Table: Communication Protocols**

| **Protocol** | **Frequency Band** | **Range (LOS)** | **Data Rate** | **Pros** | **Cons** |
| --- | --- | --- | --- | --- | --- |
| ESP32 Wi-Fi | 2.4 GHz | 100–300 m (ext.) | Moderate | Easy integration, flexible | High interference, range limitations |
| SX1278 (LoRa) | 433/868/915 MHz | Up to 10 km | Low (0.3–37.5 kbps) | Long range, low power | Low throughput, complex tuning |
| NRF24L01+ | 2.4 GHz | 1–2 km (with PA+LNA) | Up to 2 Mbps | Low latency, cost-effective | Still in congested band, moderate range |
| ESP-NOW | 2.4 GHz | Similar to Wi-Fi | Up to 250 bytes/packet | Ultra-low latency, peer-to-peer | Limited packet size, ecosystem-specific |

## 2.2 Antenna Considerations and Performance

Antenna design is critical for ensuring efficient RF communication. We explored several antenna types:

### 2.2.1 Integrated PCB Antennas

* **Pros:**
  + Already integrated into many modules.
  + Compact and low-cost.
* **Cons:**
  + Generally lower gain.
  + Limited range.

### 2.2.2 Wire Whip/Monopole Antennas

* **Pros:**
  + Improved gain and range over PCB antennas.
  + Simple design and reliable performance.
* **Cons:**
  + Can add physical bulk.
  + May require precise mounting for optimal performance.

### 2.2.3 Helical and Chip Antennas

* **Pros:**
  + Helical antennas offer circular polarization, improving performance in multipath environments.
  + Chip antennas are extremely compact.
* **Cons:**
  + Helical antennas are more challenging to tune.
  + Chip antennas may have lower efficiency compared to whip antennas.

**Comparison Table: Antenna Options for SX1278**

| **Antenna Type** | **Gain** | **Size** | **Cost** | **Ideal Application** | **Notes** |
| --- | --- | --- | --- | --- | --- |
| PCB Integrated | Low (<2 dBi) | Very small | Minimal | Prototype, low-cost designs | Limited range, fixed design |
| Wire Whip/Monopole | Moderate (3–5 dBi) | Moderate (8–10 cm for quarter-wave) | Low | Standard applications, moderate range | Easy to mount externally |
| Helical | Moderate to High (4–7 dBi) | Varies, generally larger than whip antennas | Moderate | Environments with multipath interference | Circular polarization reduces fading |
| Chip Antenna | Low to Moderate (1–3 dBi) | Very small | Moderate | Compact designs, integrated systems | Lower gain, sensitive to PCB layout |

## 2.3 Interference, Statistics, and Environmental Considerations

### 2.3.1 Interference in the 2.4 GHz Band

* **Sources of Interference:**
  + Wi-Fi routers, Bluetooth devices, microwaves, and other wireless sensors.
* **Statistical Observations:**
  + Indoor environments may see up to 40–60% packet loss due to interference.
  + Outdoor interference is less severe but still requires robust error-checking protocols.

### 2.3.2 Environmental Factors

* **Line-of-Sight vs. Non-Line-of-Sight:**
  + In open fields, systems (like ESP32 Wi-Fi or NRF24L01+) can achieve their maximum range.
  + Urban or indoor environments reduce effective range by 50% or more.
* **Weather Conditions:**
  + Rain, fog, and other adverse weather conditions can attenuate RF signals, particularly at higher frequencies.

## 2.4 Data Handling and Protocol Robustness

### 2.4.1 Error Checking and Retransmission

* **Methods:**
  + Checksums and CRCs (e.g., the FCS field in 802.11 frames).
  + Custom retransmission logic for critical commands.

### 2.4.2 Quality of Service (QoS)

* **Benefits:**
  + Ensures high-priority packets (e.g., control commands) are transmitted with lower latency.
* **Implementation:**
  + Use of QoS data frames with designated TID values to prioritize critical communications.

### 2.4.3 Security Considerations

* **Encryption:**
  + Custom encryption (e.g., AES) can be added to raw frame payloads.
* **Access Control:**
  + Using authentication methods for critical data exchanges.

# 3. Research Conclusion

After evaluating multiple communication systems and weighing their pros and cons, the following decisive choices have been made for this project:

## 3.1 Communication Device

* **Selected Module:** **SX1278 (LoRa)**
  + **Reasoning:**
    - Offers significantly longer range in open environments.
    - Operates in a less congested frequency band (433/868/915 MHz), minimizing interference.
    - Provides low power consumption, ideal for battery-operated drones.
* **Backup/Complementary Option:**
  + **ESP-NOW on ESP32** for low-latency control commands when high throughput is not required.

## 3.2 Antenna Configuration

* **Drone Antenna:**
  + A **custom-tuned copper coil antenna** or a **small external monopole** has been chosen for its lightweight and compact design.
  + **Reasoning:**
    - Minimizes added weight on the drone.
    - Sufficient for close-range telemetry when paired with a high-gain antenna on the controller.
* **Controller Antenna:**
  + A **directional high-gain antenna** (such as a Yagi-Uda) is selected.
  + **Reasoning:**
    - Focuses the signal towards the drone, compensating for any inefficiencies in the drone’s antenna.
    - Provides improved link quality and range, especially in challenging RF environments.

## 3.3 System Architecture

* **Modular Design:**
  + The system will be built in modular components: separate modules for communication (ESP32/SX1278), motor control (custom PCB with STM32), and data logging.
  + **Reasoning:**
    - Facilitates iterative development and easier troubleshooting.
    - Allows future upgrades or changes in one module without overhauling the entire system.

## 3.4 Software and Firmware

* **Custom Firmware Development:**
  + Develop custom firmware on the ESP32 to communicate with the SX1278 LoRa chip.
  + **Reasoning:**
    - Provides full control over the data being “sprayed” over the air.
    - Enables the integration of custom protocols, encryption, and QoS mechanisms tailored to drone operations.
* **Use of Existing Libraries:**
  + Leverage libraries like LoRa for rapid prototyping while developing the custom protocols for raw frames in parallel.
  + **Reasoning:**
    - Balances ease of initial development with long-term customizability.