# Case Study: Communication Bandwidth and Latency Optimization for RF Link between UAV and Ground Control Station

## 1. Problem Statement

Our defense-tech client operates fixed-wing UAV platforms for ISR (Intelligence, Surveillance, and Reconnaissance) missions. The UAVs rely on RF-based Line-of-Sight (LoS) communication to exchange telemetry, command & control (C2), and video payload with the Ground Control Station (GCS). The client faced critical communication issues:

- Bandwidth saturation when transmitting simultaneous HD video and telemetry
- High latency (>400 ms) during maneuvering and data relaying
- Packet loss and jitter due to environmental interference and antenna misalignment
- These problems posed a threat to real-time video streaming, control responsiveness, and mission safety.

## 2. Objectives

The client mandated improvements in:

- Data throughput for video & control (Target: 5–10 Mbps for HD video)
- Latency (Target: <150 ms) for round-trip control commands
- Link reliability under environmental and motion-induced interference

## 3. Our Approach

We used a **communication-aware system optimization strategy** focused on:

- RF hardware improvements (antenna, modulation schemes)
- Adaptive encoding and prioritization
- Smart data handling using compression and QoS techniques
- Real-world field validation under various terrain and mission scenarios

## 4. System Architecture Overview

RF Communication System Block Diagram:

```
      +-----------------+          +---------------------+
      | UAV Onboard Unit |<-------->| Ground Control Station|
      +-----------------+          +---------------------+
             |                              |
    +--------v--------+           +--------v--------+
    |  Radio Module   |  <--RF-->  |  Radio Module   |
    |  SDR/Transceiver|            | SDR/Receiver    |
    +--------+--------+           +--------+--------+
             |                              |
    +--------v--------+           +--------v--------+
    | Data Multiplexer|           | Demultiplexer   |
    | (C2 + Telemetry + Video)    | (QoS Priorities)|
    +--------+--------+           +--------+--------+
             |                              |
+------------v-----------+     +------------v------------+
| Flight Controller + AI |     | Command Interface + UI  |
+------------------------+     +-------------------------+
```

## 5. Key components & methodology

Hardware Optimization

We upgraded the UAV and GCS with dual MIMO antennas and SDR modules (like USRP B210) to increase signal strength and minimize multipath fading. Automatic Gain Control (AGC) dynamically tuned RF sensitivity for long-distance transmission stability.

- Upgraded to dual-antenna system with MIMO (2x2) using circularly polarized antennas to reduce multipath interference.
- Shifted from fixed-gain to AGC (Automatic Gain Control) to improve RSSI performance at long distances.
- Switched transceiver modules from legacy UHF radios to Software-Defined Radios (SDR) (e.g., Ettus USRP B210) supporting up to 20 MHz bandwidth.

RF Protocol Optimization

We implemented adaptive modulation and coding (AMC) that adjusted the signal encoding (BPSK, QPSK, 16QAM) in real time based on signal quality. This ensured maximum data throughput under changing RF conditions without sacrificing reliability.

- Implemented adaptive modulation and coding (AMC):
- Dynamically switched between QPSK, 16QAM, and BPSK based on link quality.
- Deployed TDMA-based link scheduling to reduce congestion from simultaneous video/control data bursts.

Data Handling Optimization

Video streams were compressed using HEVC (H.265) encoding, which provided near-lossless quality at 40% lower bandwidth than H.264. A data prioritization engine ensured command & telemetry data always took precedence over video in constrained bandwidth scenarios.

- Adopted H.265 (HEVC) codec for UAV video payload, reducing bandwidth by ~40% over H.264 with minimal visual loss.
- Built a real-time priority engine:
    - C2 and telemetry tagged with highest QoS level
    - Video feed compressed on-the-fly based on bandwidth feedback

Software Enhancements

We built a ZeroMQ-based middleware over UDP for real-time, low-latency messaging, with Forward Error Correction (FEC) to recover from packet drops. A jitter buffer on the GCS side helped smooth out inconsistent video and telemetry streams.

- Built middleware in C++ using ZeroMQ over UDP, enabling low-latency, connectionless transmission with fail-safe retransmissions.
- Integrated Forward Error Correction (FEC) with Reed-Solomon codes for critical telemetry packets.
- Introduced packet timestamping and jitter buffering at GCS to smooth video and C2 response.

## 6. Results

| Metric | Before | After |
|---|---|---|
| End-to-end latency | 410 ms | 112 ms |
| Video streaming bandwidth | 9 Mbps | 5.3 Mbps |
| C2 Command loss rate | 3.4% | <0.04% |
| Average link up-time | 85% | 98.6% |
| Video quality (PSNR) | 35.2 db | 34.7 db |

## 7. Learnings & Best practices

a. Effective Approaches

i. **Adaptive bitrate control** combined with **priority tagging** ensured no C2 delay even under video congestion..

ii. **MIMO + SDR combo** dramatically improved SNR and bandwidth utilization over standard UHF systems..

iii. **GStreamer pipelining with low-latency x265** provided HD video at half the previous data footprint.

b. Challenges Overcome:
   i. SDRs were more sensitive to temperature; required **active cooling** in compact UAV bays.
   ii. Codec selection needed **hardware acceleration (ARM NEON)** for real-time encoding on low-power CPUs

## 8. Tools & Tech Stack Used

| Category | Tools |
|---|---|
| RF Hardware | Ettus USRP B210, LimeSDR, MIMO antennas |
| Protocol & Link Layer | GNU Radio, SDR++, OpenAirInterface |
| Data Compression | GStreamer, x265 encoder, FFmpeg |
| Real-Time Comm | ZeroMQ, UDP Sockets, FEC libraries |
| Testing | iPerf3, Wireshark, RF channel emulator (Spirent) |
| Embedded Dev | Yocto Linux (UAV), Ubuntu GCS, C++, Python |

## 9. Conclusion

By optimizing across hardware, protocol, and software layers, our solution delivered:

- **Low-latency, high-reliability RF communication**
- **Scalable bandwidth management for dual-payload UAVs**
- Enhanced **situational awareness and operator confidence**

This architecture is now being replicated for **multi-UAV missions**, with provisions for future **mesh-based communication and LTE/5G hybrid links**.