Mobile Network Driven Limitless Range Telemetry System for Autonomous UAVs

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Abstract: This paper introduces an advanced telemetry system for autonomous UAVs using the MAVLink protocol and secure VPN tunneling to communicate with ground control stations via 4G mobile networks. By leveraging mobile infrastructure, the system achieves extended range for real-time data transmission and control, overcoming traditional radio frequency limitations. The integration of VPN ensures a secure and private communication channel, while 4G connectivity enables reliable and low-latency operations. Extensive testing confirms its effectiveness for applications in surveillance, environmental monitoring, and logistics. These characteristics provide a distinct advantage in dense urban environments in terms of cost, interference susceptibility, and range.

1 INTRODUCTION

The convergence of unmanned aerial vehicles (UAVs) with advanced communication networks presents a transformative opportunity for communication and innovation. Advanced communication networks offer ultra-high bandwidth, low latency, and massive network capacity, while UAVs provide flexible aerial platforms. This combination has the potential to revolutionize various sectors, from enhancing connectivity in underserved areas to enabling real-time monitoring and data collection in diverse applications. (Wazid, et al. 2020), (Mishra, et al. 2020), (Festag, et al. 2021)

This paper explores a 4G-based VPN Powered telemetry system as a robust alternative to traditional radio frequency-based communication for UAVs. It highlights the advantages of the proposed system, including enhanced range, reduced susceptibility to interference, and cost-effectiveness in dense urban environments. A detailed performance study evaluates the system across various parameters, showcasing its performance and reliability. The design and working principles of the demonstrator platform are presented to illustrate the practical implementation. Based on the findings and unique traits of this system, the paper identifies key application areas where this technology offers significant advantages, such as urban surveillance, logistics, and environmental monitoring. (Jin, et al. 2021), (Hassija, et al. 2021), (Fakhreddine, et al. 2022), (Pocovi, et al. 2018)

2 EASE OF USE

The proposed system is designed with ease of use as a central focus, ensuring seamless integration into existing UAV workflows. By utilizing widely available 4G mobile networks and standard VPN configurations, the system eliminates the need for specialized hardware or complex setup processes associated with traditional radio frequency systems. Its plug-and-play architecture simplifies deployment, while intuitive connectivity through VPN tunneling ensures secure and reliable communication with minimal operator intervention. Our system enables operators to securely control multiple drones simultaneously from anywhere in the world, leveraging the flexibility of 4G connectivity and VPN tunneling. A custom-designed graphical user interface (GUI) provides an intuitive and user-friendly platform for managing UAV operations. This streamlined approach not only reduces operational complexity but also enables rapid scala-

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bility across diverse applications, making it an accessible and practical solution for both novice and experienced UAV operators. (Bakirci, 2023), (Zulkifley, et al. 2021), (Gorrepati and Guntur 2021)

3 CONCEPT

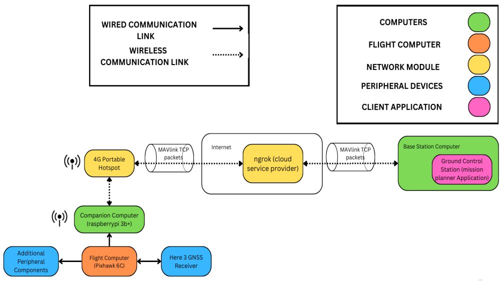

Figure 1: System Architecture

The above figure 1 illustrates a user-friendly UAV system leveraging 4G networks and VPNs to eliminate specialized hardware and complex setups. Its plug-and-play design ensures easy deployment, while secure tunneling enables reliable multi-drone control globally. A custom GUI simplifies operations, reducing complexity and enhancing scalability for all users.

4 COMMUNICATION PROTOCOLS

4.1 VPN (Virtual Private Network)

A Virtual Private Network (VPN) is a technology that establishes a secure and encrypted connection over a less secure network, such as the Internet. VPNs are widely used to protect private data, provide secure remote access to systems, and ensure privacy by masking the user's IP address. In our Internet-based drone system, VPN is utilized to enhance security, privacy, and accessibility:

1. **Secure Remote Access:** A VPN ensures encrypted communication between the ground control station and the drone, protecting it from unauthorized access.
2. **IP Masking and Privacy Protection:** The VPN hides the IP addresses of both the drone and the ground control station, safeguarding the drone's location and data from potential attackers.
3. **Improved Reliability:** Using a VPN server helps prevent disruptions caused by network instability or interference, maintaining a stable connection.
4. **Centralized Network Management:** A VPN allows multiple drones to securely connect to a central server, enabling efficient management and coordination of drone operations from the ground.

4.2 MAVLink (Micro Air Vehicle Communication Protocol)

MAVLink (Micro Air Vehicle Communication Protocol) is a lightweight messaging protocol designed for communication between unmanned aerial vehicles (UAVs), ground control stations (GCS), and onboard systems. It is widely used in the drone ecosystem due to its efficiency, flexibility, and scalability. MAVLink supports both telemetry and command-and-control functionalities, enabling seamless communication in UAV systems.

1. **Multi-Channel Communication:** MAVLink supports communication over multiple channels, such as serial, UDP, and TCP. This enables flexibility in the choice of communication mediums, whether over wired or wireless networks.
2. **Heartbeat Mechanism:** The protocol includes a heartbeat message that is periodically exchanged between the UAV and GCS. This mechanism ensures that the connection is active and helps in detecting link failures promptly.
3. **Extensibility:** MAVLink allows the addition of custom message definitions, enabling developers to extend the protocol to suit specific application requirements without compromising compatibility with existing systems.
4. **Real-Time Data Exchange:** The protocol facilitates real-time exchange of telemetry data, including GPS coordinates, battery status, attitude, and sensor readings, enabling precise monitoring and control of the UAV.
5. **Command and Control:** MAVLink supports sending commands such as takeoff, landing, waypoint navigation, and parameter updates, enabling comprehensive control over UAV operations from the GCS.

5 IMPLEMENTATION OF THE PROPOSED COMMUNICATION SYSTEM

The proposed communication system leverages 4G connectivity and VPN integration to establish a secure communication channel between the drone and the ground control station (GCS). The implementation steps are detailed as follows:

5.1 Establishing Internet Connectivity through 4G

The Raspberry Pi (RPI) onboard the drone was configured to connect to the internet using a 4G portable hotspot. The 4G network provides reliable internet access in areas covered by cellular networks, ensuring long-range communication capabilities.

5.2 Setting Up a VPN for a Secure Private Network

To establish a private communication channel, both the RPI and the ground control laptop (GCS) were connected to the same Virtual Private Network (VPN). The following steps were taken:

1. **VPN Client Installation:** A VPN client was installed and configured on both devices to ensure secure connectivity.
2. **VPN Server Configuration:** A centralized VPN server was set up to manage connections, assigning unique private IPs to the devices.

This configuration created a virtual local network, allowing seamless communication between the drone and the GCS while maintaining data security.

5.3 Enabling Data Transmission using TCP and MAVLink Protocol

Telemetry data and commands were transmitted using:

- **Transmission Control Protocol (TCP):** Ensures reliable and ordered data delivery.
- **MAVLink Protocol:** A lightweight communication protocol designed for UAVs.

The VPN-assigned IP address of the RPI was used as the endpoint for accessing telemetry data and sending commands. Furthermore, TCP facilitated both unicast and multicast of MAVLink messages:

1. **Unicast and Multicast:** TCP allows the distribution of MAVLink messages to multiple ports. For instance, if the RPI's VPN IP is `10.8.0.5`, it can transmit messages to ports specified by the user, such as `14441`, `14442`, and so on.
2. **Scalable Access:** This setup enables multiple ground control stations or tools to access the drone's data and commands simultaneously.

5.4 Configuring Ground Control Access

The ground control laptop (GCS) was configured to use the RPI's VPN IP address for communication with the drone. Key functionalities include:

1. **Real-Time Monitoring:** Operators can monitor telemetry data, including position, altitude, battery status, and video streams, in real time.

Figure 2: Real-Time Video Stream

Figure 2 illustrates a snapshot of a live video stream captured just before landing. The video streaming is facilitated through a VPN using WebRTC, ensuring secure and reliable transmission. These streams are globally accessible to any client connected to the VPN, enabling real-time monitoring from remote locations.

2. **Command Transmission:** Commands such as takeoff, waypoint navigation, and landing can be sent securely via the VPN.

The integration of TCP and the VPN ensured low latency and reliable data exchange between the drone and the GCS.
This implementation demonstrates the integration of 4G and VPN technologies to establish a robust and secure communication system for drones, enabling remote operations over long distances with scalable access to MAVLink data.

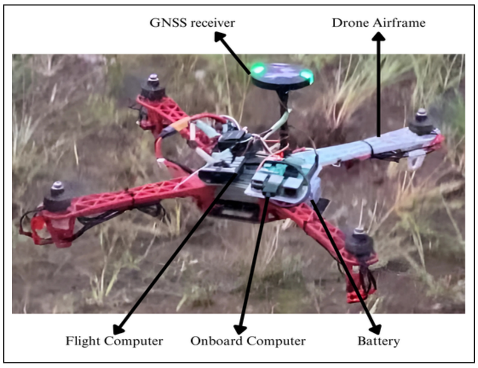

Figure 3: UAV Demonstrator

6 PERFORMANCE ANALYSIS

6.1 Range

- **Mobile Network-Based System** The 4G based system offers worldwide coverage, relying on cellular network availability. Its signal strength depends on the proximity to the cellular towers and the level of network congestion, while the range is practically unlimited within the areas covered by the network.
- **Conventional RF Telemetry System** RF-based systems have a range that depends on transmission power, frequency, antenna design, and environmental conditions, with RSSI degrading logarithmically due to path loss. Coverage is limited by line of sight and obstructions, as signal strength diminishes with distance and environmental factors. The effective range is typically up to 1–2 km under ideal conditions, but is significantly reduced by obstacles

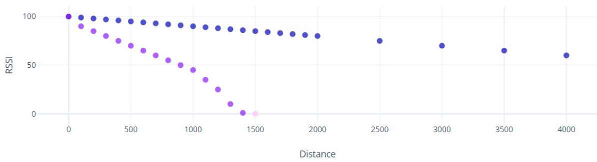

Figure 4: Distance vs RSSI Graph

- **Inference:** From Figure 4, The mobile 4G based telemetry system offers superior range and consistent signal strength compared to the 433 MHz RF system, especially with existing cellular infrastructure. Although the RF system provides low-latency communication within a limited range and ideal conditions, its performance degrades rapidly with distance and obstructions. In contrast, the mobile network system maintains robust connectivity over vast distances.

6.2 Latency

- **Mobile Network-Based System**
  Latency in cellular systems is influenced by encoding/decoding time, transmission time, and processing delays, with typical values ranging from 50 to 150 ms under ideal conditions to more than 300 ms in weak signals. Distance also impacts latency due to propagation delays and handovers, with greater distances leading to slightly higher latency.
- **Conventional RF Telemetry System**
  Latency in RF systems depends on encoding/decoding time, transmission time, and receiver processing delays, typically ranging from 10-50 ms for short ranges (0-100m) to 50–100ms for medium ranges (100m–1km). Although distance has less impact at shorter ranges, increasing distance can cause significant signal degradation and retransmissions, adding to latency.

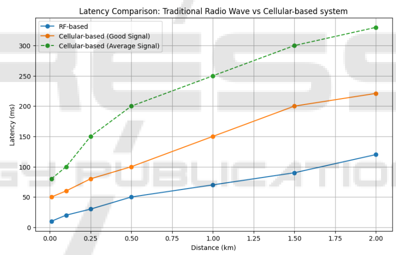

Figure 5: Distance vs Latency Graph

- **Inference:** Latency analysis from Figure 5 highlights the advantages and limitations of RF-based and cellular-based telemetry systems over varying distances. RF systems have lower latency at short distances, starting at 10 ms compared to 50 ms for cellular systems, but the difference is minimal. As distance increases, the latency gap narrows, with RF reaching 120 ms and cellular systems at 220–330 ms at 2 km, depending on signal quality. This diminishing difference makes cellular systems more advantageous for longer ranges, offering reliable performance with slightly higher latency.

6.3 Noise

Noise refers to unwanted disturbances that interfere with the transmission signal, resulting in a reduction in video quality and stability.

- **Mobile Network-Based System** Mobile networks, such as 4G and 5G, offer high-quality video transmission with minimal noise due to their error correction mechanisms and adaptive bitrate control. These systems are well-suited for long-range operations and maintain consistent performance even in the presence of moderate interference. They support high-definition video (up to 4K), ensuring reliability across diverse environments.
- **Conventional RF Telemetry System** Analog RF-based systems, such as the TS835, are more prone to noise, which can cause the video to become grainy and unstable. These systems perform adequately over short distances with low interference, but suffer significant degradation in quality and reliability as distance increases. Signal quality quickly decreases in areas with high interference or weak signals, limiting their effectiveness.

6.4 Additional Factors

1. **Cost**
   Cellular telemetry systems are more cost-effective, with a typical setup priced at $50, compared to $200 for RF systems. This is due to the use of existing mobile infrastructure and mass-produced hardware, which reduces both initial and long-term costs. RF systems, on the other hand, require specialized equipment, leading to higher expenses.
2. **Ready To Operate**
   Cellular-based systems are plug-and-play, offering ease of use by simply connecting to existing mobile networks without requiring a complex setup or configuration. This user-friendly nature makes them ideal for quick deployment. In contrast, RF systems require a more intricate setup, including specific hardware configuration, antenna alignment, and frequency management, which can be time-consuming and challenging for users, making them less convenient for everyday use.

7 APPLICATIONS

The advanced telemetry system that leverages 4G mobile networks and secure VPN tunneling offers several compelling applications, particularly in urban areas where the mobile network infrastructure is robust. In dense urban environments, where traditional RF-based systems face significant challenges with signal degradation and interference, this system can provide a reliable and cost-effective solution for package delivery. The extensive mobile infrastructure reduces operational costs, as it leverages existing cellular towers and networks, eliminating the need to set up dedicated communication systems. Furthermore, with low susceptibility to signal disturbances, this system ensures efficient real-time communication and control, making it ideal for urban logistics and e-commerce applications.

Another promising application is in scenarios where off-site operation and monitoring of UAVs are required. This system enables operators to control and monitor UAVs from anywhere in the world, even from different countries. For example, a UAV tasked with monitoring infrastructure in a remote region could be operated by an expert based in another country, providing flexibility and efficiency. This ability to manage UAVs from distant locations expands the potential for global collaborations, remote diagnostics, and emergency operations, with minimal physical presence required on site.

In addition, the system is invaluable for industrial surveys and disaster relief operations. In industries, UAVs can perform real-time inspections of machinery, pipelines, and construction sites, enhancing safety and reducing manual effort. In disaster relief, the system enables rapid deployment, live situational awareness, and supply delivery, ensuring efficient coordination even in challenging environments. Its secure, low-latency communication supports critical operations seamlessly.

8 CONCLUSION

In conclusion, this study has introduced and successfully implemented a 4G-based telemetry system for autonomous UAVs, leveraging the MAVLink protocol and VPN integration to enable secure, reliable, and low-latency communication. The proposed system demonstrates clear advantages over traditional RF-based systems by extending operational range, enhancing communication security, and ensuring robust performance in dense urban environments. The integration of a Raspberry Pi onboard, coupled with seamless connectivity to a ground control station through mobile infrastructure, offers unparalleled flexibility for global remote control and monitoring. Extensive testing validates the suitability of the system for critical applications such as surveillance and logistics. These innovations establish a versatile and scalable platform that meets the evolving demands of modern drone operations, paving the way for future advancements in drone technology.

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