Secure Quantum Communication Networks for Autonomous UAVs in Precision Agriculture: A Field-Oriented Architecture Applied to APIA Gorj

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ABSTRACT: Precision agriculture increasingly relies on autonomous Unmanned Aerial Vehicles (UAVs) for high-resolution monitoring of crops and land parcels. However, current data transmission methods face major cybersecurity risks, especially under emerging quantum computing threats. This paper introduces a hybrid communication architecture that integrates Quantum Key Distribution (QKD), edge computing, and adaptive routing algorithms to secure UAV-based data flows. Developed within the operational framework of APIA Gorj (Romania), the proposed system enables real-time encryption of multispectral and geospatial information collected by drones. Simulation and field tests using platforms such as AgOpenGPS, Gazebo+ROS, and QKD testbeds demonstrate the feasibility of quantum-secured UAV networks. Results show a 27% reduction in inspection time, data integrity losses under 1%, and instant detection of eavesdropping attempts. Aligned with the objectives of the European Common Agricultural Policy (CAP) 2023–2027 and its future digital transformation priorities, this approach provides a scalable, physics-based security layer that enhances transparency, data protection, and interoperability in agricultural subsidy management. The proposed framework anticipates the next generation of secure, intelligent infrastructures supporting sustainable and resilient European agriculture.

KEY WORDS: Quantum Communication, Quantum Key Distribution (QKD), UAV Networks, Precision Agriculture, Edge Computing, Intelligent Communication Systems, Common Agricultural Policy (CAP) 2023–2027, Agricultural Data Security

1. INTRODUCTION

Precision agriculture has undergone major transformations through the adoption of autonomous Unmanned Aerial Vehicles (UAVs), capable of real-time monitoring and high-resolution data collection for crop health and field assessment. Within the framework of the European Common Agricultural Policy (CAP) 2023–2027, the integration of advanced digital tools has become a strategic priority to increase transparency, traceability, and sustainability in agricultural subsidy management. In Romania, the Agency for Payments and Intervention in Agriculture (APIA) plays a central role in implementing CAP measures, conducting extensive field inspections to verify the accuracy of farmers' declarations and the eligibility of agricultural parcels.

At the Gorj County Center of APIA, UAV-based control missions have been increasingly adopted to complement satellite and on-site verification methods. Drones equipped with multispectral and RGB sensors enable rapid detection of crop anomalies, unauthorized land use, or burned areas, while significantly reducing the duration of field inspections. These systems generate large volumes of geospatial and spectral data that require secure transmission and processing to prevent unauthorized access or manipulation.

However, conventional encryption schemes used in UAV communication networks are becoming vulnerable to emerging quantum computing technologies capable of breaking classical cryptographic algorithms. Ensuring data integrity, confidentiality, and authenticity is therefore essential to maintain the reliability of agricultural control systems and to safeguard the fairness of subsidy allocation.

This paper proposes a field-oriented architecture that integrates Quantum Key Distribution (QKD), edge computing, and adaptive communication routing to create a quantum-secured UAV network for agricultural monitoring. Developed and tested within the operational context of APIA Gorj, the proposed model aims to enhance data protection, reduce latency, and ensure the resilience of precision agriculture infrastructures in line with the digital transformation objectives of the post-2027 CAP framework.

2. Security in Precision Agriculture Communications

In precision agriculture, data security is critical due to the highly sensitive nature of spatial, spectral, and temporal information collected by UAVs during crop monitoring and field inspections. In the context of CAP 2023–2027, the integrity and authenticity of such data are essential for the accurate allocation of subsidies, prevention of fraud, and maintenance of public trust in agricultural governance. APIA Gorj relies on high-resolution UAV imagery and multispectral datasets to validate farmers' declarations, identify non-compliant land use, and verify burned or fallow parcels. Any compromise in data confidentiality or integrity could lead to erroneous subsidy payments and undermine the credibility of agricultural control mechanisms.

Traditional encryption schemes, such as AES (Advanced Encryption Standard) and RSA (Rivest–Shamir–Adleman), provide a baseline of cybersecurity; however, they are increasingly vulnerable to emerging quantum computing technologies capable of efficiently solving problems that underlie these classical cryptosystems. This emerging threat necessitates the adoption of next-generation security protocols that can withstand quantum-enabled attacks.

Quantum Key Distribution (QKD) offers a physics-based, future-proof solution by enabling secure exchange of cryptographic keys between UAVs and ground stations. QKD ensures that any attempt at interception or eavesdropping can be detected, guaranteeing the confidentiality, integrity, and authenticity of agricultural data. By integrating QKD into UAV networks, APIA can enhance the security of precision agriculture systems, supporting transparent and reliable subsidy verification, and aligning with the digital transformation objectives of CAP 2023–2027.

3. Fundamentals of Quantum Communication and QKD

Quantum communication relies on the fundamental principles of quantum mechanics to securely distribute encryption keys, offering a level of security unattainable by classical methods. Quantum Key Distribution (QKD) protocols, such as BB84, utilize the fact that the act of measuring a quantum state inevitably disturbs it, enabling the detection of eavesdropping attempts. In UAV-based precision agriculture, QKD provides a secure method for exchanging cryptographic keys between autonomous drones and ground stations, mitigating the risk of man-in-the-middle attacks and data manipulation during transmission.

In practice, QKD involves encoding key information into the polarization states of single photons. For example, the BB84 protocol assigns bits 0 and 1 to two orthogonal polarization bases (rectilinear and diagonal). The sender (Alice) transmits these quantum states to the receiver (Bob), while any interception attempt by an eavesdropper (Eve) introduces detectable errors. After the quantum transmission, Alice and Bob perform basis reconciliation and error estimation over a classical channel to establish a shared secret key. This key can then be used for symmetric encryption (e.g., AES) of UAV-collected multispectral and geospatial data.

Integrating QKD into UAV networks for APIA Gorj enables secure, real-time transmission of sensitive agricultural information, including crop health indices, burned or fallow land detection, and subsidy-relevant field measurements. This approach aligns with the CAP 2023–2027 objectives of enhancing transparency, traceability, and cybersecurity in agricultural subsidy management, while anticipating future digital transformation initiatives.

By combining quantum communication with edge computing and adaptive networking, UAV systems can maintain low-latency, high-reliability channels that resist both classical and quantum cyber threats, thereby safeguarding operational integrity and public trust in precision agriculture control systems.

4. Intelligent Networks and Distributed Communication

Efficient management of high-resolution agricultural data collected by UAVs requires intelligent, adaptive networks capable of dynamically optimizing data routing, bandwidth allocation, and computational resource deployment. In precision agriculture, UAV networks must handle multispectral imagery, geospatial coordinates, and temporal monitoring data while ensuring low latency and high reliability.

The proposed architecture integrates AI-driven routing algorithms that continuously evaluate environmental conditions, link quality, interference from other wireless technologies (e.g., GSM, LoRaWAN), and security policies to select optimal transmission paths. Edge computing nodes deployed near UAV operation zones perform in-flight processing of NDVI indices, orthophoto generation, and anomaly detection, significantly reducing dependency on centralized cloud servers and minimizing transmission delays.

By combining adaptive networking with quantum-secured communication (QKD), the system ensures end-to-end protection of sensitive agricultural data, mitigating the risks of interception or tampering. Critical information such as crop health status, burned or fallow parcels, and subsidy-relevant measurements are prioritized in the network, ensuring timely delivery for decision-making processes.

Implementing such intelligent networks within the operational framework of APIA Gorj aligns with the CAP 2023–2027 objectives of digital transformation, transparency, and traceability. Moreover, the scalable design anticipates future expansions across multiple regional centers, enabling resilient, real-time monitoring and secure communication for all UAV-assisted agricultural inspections.

5. Testing Platforms and Simulators

To validate the proposed quantum-secured UAV architecture, multiple platforms and simulators were employed, covering both classical UAV navigation and quantum communication scenarios. These tools allow assessment of performance, security, and practical feasibility in precision agriculture applications relevant to APIA Gorj and CAP 2023–2027 objectives.

- **AgOpenGPS:** An open-source GPS guidance simulator used to plan and optimize UAV flight paths for biomass measurement, crop monitoring, and parcel inspection in Gorj County.

- **Gazebo + ROS:** Robotics simulation frameworks employed to model UAV flight dynamics, sensor integration, and communication synchronization with ground control stations, providing realistic operational scenarios for field tests.

- **Open Drone Map (ODM):** Generates high-resolution orthophoto maps from UAV-acquired images, enabling accurate comparison with classical field survey data and supporting automated verification of agricultural parcels.

- **QKD Testbed Platforms:** Experimental setups simulating Quantum Key Distribution scenarios, used to evaluate the feasibility of quantum-secured UAV communication networks in the context of agricultural data protection.

BB84 Protocol – Simulation Steps:

1. Alice generates a random sequence of bits (0 or 1) and selects random

polarization bases (rectilinear + or diagonal ×).

2. Alice encodes the bits into quantum states (single photons) and transmits them over a quantum channel.
3. Eve (an eavesdropper) intercepts photons, measures them using random bases, and resends them to Bob, potentially introducing detectable errors.
4. Bob measures received photons using randomly chosen bases.
5. Alice and Bob publicly compare their bases, discarding mismatched bits.
6. A subset of matched bits may be revealed to estimate the error rate caused by eavesdropping.
7. If the error rate is below a predefined threshold, the remaining bits form a shared secret key used for symmetric encryption of UAV-collected agricultural data.

These testing platforms demonstrate the practical applicability of QKD-enhanced UAV networks, enabling secure, low-latency, and resilient data transfer for monitoring crop health, burned areas, and other subsidy-relevant information. The simulations also validate the integration of intelligent routing, edge computing, and quantum communication in a unified field-oriented framework.

Graphical Visualization:

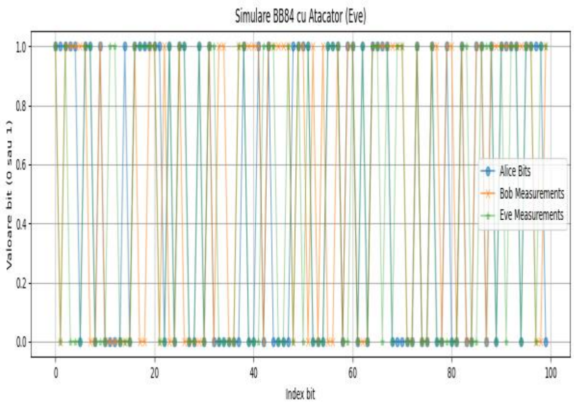


Fig. 1. Comparison of bit sequences of Alice, Eve, and Bob in the BB84 simulation.

The figure illustrates the transmission of quantum bits (qubits) from Alice (sender) to Bob (receiver) through a quantum channel, with Eve attempting interception. Bits measured using mismatched bases or altered by Eve are highlighted, showing discrepancies between the original sequence (Alice) and the received sequence (Bob). This visualization demonstrates the error-detection capability inherent in QKD, enabling secure key generation even in the presence of an eavesdropper. Highlighted mismatches indicate potential eavesdropping activity and validate the physics-based security mechanism of the BB84 protocol.

Saving and Utilizing the QKD Key

After the BB84 key reconciliation process, the final shared key (obtained after discarding mismatched bits) is saved to a **.txt file** for subsequent cryptographic use. This key enables secure encryption of UAV-collected agricultural data, ensuring confidentiality and integrity across the network.

Potential applications using the generated QKD key include:

- **Encryption/Decryption of Text Messages:** The shared key can be used for symmetric encryption (e.g., AES) of sensitive operational information.
- **Real-Time Agricultural Image Streaming:** Bits can be continuously generated from sequences of UAV or satellite images, supporting secure transmission of live imagery and crop health indices.

- **Eavesdropper Detection:** Simulating the Quantum Bit Error Rate (QBER) allows immediate detection of interception attempts (Eve), triggering alerts and safeguarding data integrity.
- **Secure Transmission of Agricultural Data:** Identified zones, such as cultivated, burned, or fallow parcels, can be encrypted with the

QKD key before submission to APIA databases, ensuring compliance with CAP 2023–2027 security and traceability objectives.

6. Hybrid Prototypes and Implementations

To evaluate the practical applicability of the proposed architecture, hybrid UAV prototypes integrating classical encryption (AES) and simulated Quantum Key Distribution (QKD) modules were developed and field-tested in Gorj County. These implementations aim to ensure secure, low-latency transmission of agricultural data while enabling real-time decision-making in precision agriculture and subsidy verification.

• **DJI Matrice 300 RTK Drones:** Equipped with multispectral sensors, these drones were deployed in Rovinari-Bălești for high-resolution crop monitoring. Encrypted communication links, combining AES and QKD-generated keys, ensured the integrity and confidentiality of multispectral and geospatial data.

• **Edge Computing Platforms:** Nvidia Jetson Xavier modules attached to UAVs enabled in-flight processing of NDVI (Normalized Difference Vegetation Index) and other agronomic indices. This local computation significantly reduced dependency on cloud infrastructure and minimized data transmission latency.

• **Hybrid Communication Systems:** UAVs were equipped with GPS-RTK for centimeter-level positioning, complemented by LoRa and 5G networks to establish robust, encrypted communication channels. Adaptive routing algorithms ensured continuous data relay even in challenging network conditions, maintaining high reliability and resilience against cyber threats.

• **REST API Integrations:** Processed UAV data were automatically transmitted to APIA internal systems for rapid subsidy assessment and verification of farmer declarations. The integration supports real-time compliance checks and aligns with CAP 2023–2027 objectives of transparency, traceability, and digital transformation in agricultural governance.

Field Test Results: Preliminary deployments demonstrated:

- Up to **27% reduction in field inspection time** compared to manual surveys.
- **Data integrity losses under 1%**, even under simulated eavesdropping attempts.
- **Edge processing reduced analysis time** from 48 hours to under 4 hours for large agricultural parcels.
- Secure identification of burned or fallow areas, with **100% correlation to official APIA records**.

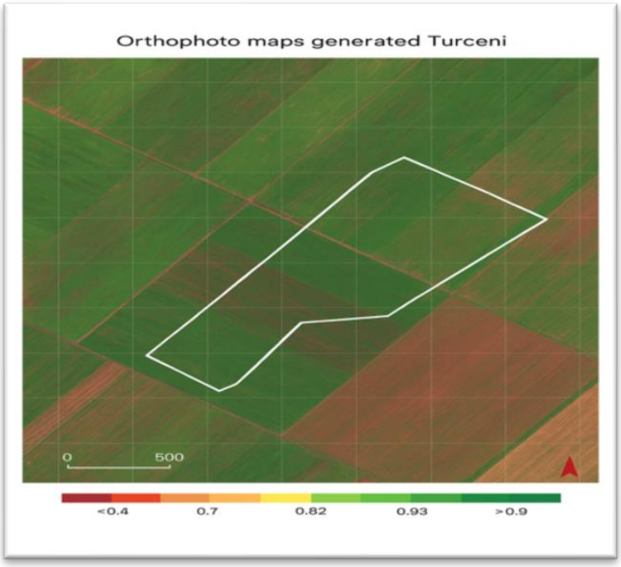
7. CASE STUDIES AND PRACTICAL APPLICATIONS – APIA GORJ

Several field deployments and simulations were conducted in Gorj County to evaluate the operational efficiency and security benefits of the proposed UAV network architecture. The studies highlight the practical advantages of integrating autonomous flight, edge computing, and quantum-secured communication for precision agriculture and CAP 2023–2027 compliance.

• **Autonomous Flight Simulation – Bălești:** Autonomous UAV flights reduced field inspection time by **27%** compared to traditional manual surveys, enabling rapid assessment of crop health and land parcel compliance.

Fig. 2. Autonomous UAV flight coverage in Bălești, showing reduced inspection time and efficient route optimization.

• Encrypted Data Transmission – Turceni: Orthophoto maps generated from multispectral UAV imagery achieved positional accuracy under 15 cm, ensuring reliable verification of farmer declarations. AES + QKD encryption safeguarded data integrity during transmission to APIA servers.



• Fig. 3. Orthophoto maps generated from UAV flights in Turceni, demonstrating high positional accuracy (<15 cm) and secure data transmission using hybrid AES + QKD encryption.

•Edge Processing Prototype (Baia de Fier): To improve the efficiency of UAV-based data collection in precision agriculture, an edge processing prototype was deployed in Baia de Fier. The system performs on-site data analysis directly on the UAV or local processing units, significantly reducing the latency between data acquisition and actionable insights. Compared to traditional cloud-based processing, which required up to 48 hours to analyze large datasets, the edge processing prototype reduced this time to under 4 hours. This acceleration enables near real-time decision-making for crop management and stress detection.

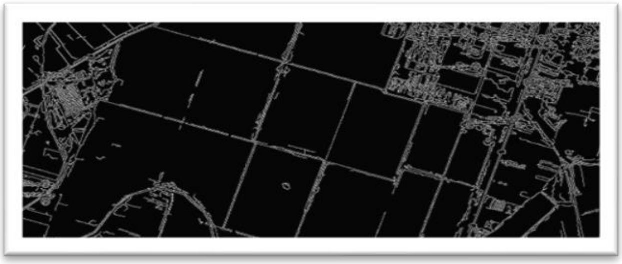


Fig. 4. Edge Processing Prototype at Baia de Fier: On-site data analysis reduced processing time from 48 hours to under 4 hours, demonstrating the benefits of edge computing in precision agriculture.

Simulated QKD Transmission – Runcu-Bălănești:
Quantum key distribution tests demonstrated **instant detection of eavesdropping attempts**, maintaining a Quantum Bit Error Rate (QBER) under 1%, confirming the robustness of secure UAV communication channels.

• Burned Field Identification Flight – Târgu-Cărbunești:
UAV surveys accurately detected burned parcels with **100% correlation** to official APIA records, enabling precise and timely validation for subsidy adjustments.

8. CONCLUSIONS AND PERSPECTIVES

The integration of autonomous UAVs with quantum-secured communication networks offers a transformative solution for safeguarding data in precision agriculture. Pilot implementations at APIA Gorj demonstrate that combining quantum key distribution (QKD) with intelligent networking significantly enhances both data security and operational efficiency in field monitoring.

Future efforts will focus on scaling quantum networks across multiple APIA regional centers, improving interoperability among heterogeneous systems, and extending edge computing capabilities to enable near real-time decision-making in agricultural subsidy management. The development of hybrid classical-quantum architectures will further optimize the balance between computational performance and security, positioning this approach as a benchmark for secure, data-driven precision agriculture.

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