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Mobile-Enabled Internet of Drones: An Initiative Project for Advancing Drone Connectivity in 5G and Beyond 5G

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Abstract:

This research explores the transformative potential of mobile-enabled drone communications as a foundational technology for the Internet of Drones (IoD). The study emphasizes the integration of terrestrial mobile networks, addressing the critical requirements of safe, reliable, and scalable drone operations. With the advent of advanced mobile networks—such as 5G, Beyond 5G (B5G), and pre-6G—the research highlights how ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC) capabilities can address challenges such as interference, asymmetric data flows, and real-time traffic management. The methodology combines theoretical modeling, simulation, and real-world experimentation through the establishment of a comprehensive testbed. The testbed integrates drones with terrestrial mobile networks, demonstrating uplink throughput, latency performance, interference mitigation, and robust connectivity under diverse conditions. Key findings reveal that mobile networks can effectively support high-throughput, low-latency drone communication in both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) scenarios, with scalable solutions to overcome interference and environmental challenges. Additionally, drone-assisted communication and integration with Unmanned Aircraft System Traffic Management (UTM) systems underscore the feasibility of real-time tracking, collision avoidance, and secure operations. This research contributes to advancing IoD systems by providing practical insights into mobile networks as a foundation for future mobile ecosystems. By bridging theoretical concepts and experimental validations, the study offers a pathway for policymakers, industry stakeholders, and researchers to enable a globally connected IoD ecosystem.

Keywords: Internet of Drones (IoD), Mobile-Enabled Drone Communication, 5G and Beyond (B5G), Drone Communication Testbed

INTRODUCTION

DRONES have long been the focus of governments and academia for security and defense purposes. In recent years, there has been growing interest in these aerial systems for commercial applications such as precision farming, inventory management, last-mile deliveries, and, in general, for instant aerial photography and video making. Wide-area secure wireless network connectivity is required to safely expand drone operations and unlock the potential of drone technology for commercial applications. Technically, the mobile research community believes that mobile networks are well suited to provide the necessary connectivity for drones [1]. To ensure reliable airborne communication, the connectivity performance of terrestrial mobile networks has been studied, along with the additional capabilities these networks can offer for drone operations and management. It is expected that 6G will bring a full-integrated platform for connected things and automation systems from autonomous cars to drones with stringent and diverse requirements in terms of reliability, latency, data rate, and energy efficiency [2].

In early 2016, many researchers identified that one key area to study in the 3GPP Release 15 was to enable mobile network connected drones. During that period of time, the 3GPP study assessed the performance of LTE networks supporting aerial vehicles with up to the 3GPP Release 14 functionality. The study was completed and the outcomes were documented in the 3GPP technical report TR 36.777 including comprehensive analysis, evaluation, and field measurement results [3]. The 3GPP TR 36.777 has become a definitive guide for mobile network connected drones, and has been widely cited by academia, industry, and regulatory organizations. The 3GPP study concluded that it is feasible to use existing LTE networks to provide connectivity to drones, but there may be challenges related to interference as well as mobility [1]. The challenges become more visible when the density of drones is high. Both implementation and specification-based enhancements were identified during the 3GPP study to address these issues.

After completing the study item, a follow-up work item was approved at the 3GPP RAN plenary meeting in 2017. The objective of the work item was to specify features that can improve the efficiency and robustness of terrestrial LTE networks for delivering more efficient connectivity solutions for drones. This 3GPP work item was completed in 2018 [4]. In addition to the 3GPP Release 15 work on LTE Aerials in RAN, 3GPP SA studied the remote identification of unmanned aerial systems (UAS) in Release 16, and continues to investigate more aspects including connectivity, identification, tracking, application layer support, and security in Release 17. After the completion of the 3GPP Release 15 work on connected drones, we have seen a surge of field trials for connected drones around the globe by major operators and vendors [5]. Various industry organizations have set up special drone interest groups to develop new use cases and help create an open and trusted regulatory environment. Besides, GSMA has been cooperating to align mobile and aviation industries. The world has also witnessed growing efforts from governments to safely integrate civil and public drone operations into airspace systems [1], [4].

The development in microprocessors, control algorithms, and the technology that goes into creating drones are some of the factors that have not only drastically reduced costs but have also created a rich ecosystem of companies dedicated to providing drone-related services. One of the enabling technologies that have driven the significant advancements in drone technology is the use of GPS technology. The use of direct satellite navigation also provides the low-cost inertial data that can be used to support autonomous indoor navigation. Cameras, video streaming, and image analysis software are other technologies that have sufficient maturity to allow for the wide implementation of many autonomous applications [6],[7].

Fast and low-power integrated circuitry with dedicated software and hardware algorithms and the use of lightweight drones capable of flying for more than half an hour at a fraction of the cost have brought to bear the power of these technologies directly on every professional, consumer, and non-profit organization. From the air, a camera can provide live and high-definition resolution of what is happening below, as well as enable video analytics of what is being seen. The low-latency video streaming capability provides efficient remote piloting [6],[7]. Drones are found extremely useful to replace humans or manned aircrafts in missions that are dull, dirty, and dangerous. Driven by the continuous cost reduction in drone manufacturing, as well as the recent government efforts in practical drone-related regulations in many countries, the demand for drones is expected to exponentially explode in the near future. For example, the global drone market was valued at 18.14 billion U.S. dollars in 2017, and is projected to reach 52.30 billion U.S. dollars by 2025 [8].

To realize the unprecedentedly large-scale deployment of drones in the future, it is of utmost importance to ensure that all drones can fly safely, which requires ultra-reliable and secure communication links between drones and their ground control stations. Moreover, high-rate drone-ground communication links are also in need for various rate-demanding applications, e.g., when drones need to timely send their captured high-resolution photo/video to the remote users on the ground.

The need to reach a global ubiquitous coverage establishes the connectivity of the future via universal and seamless accessibility. Through the space-air-ground integrated network architecture, the space-air-ground convergence advantages in each segment can be equipped to support various drone applications and services as summarized in Fig. 1 [9].

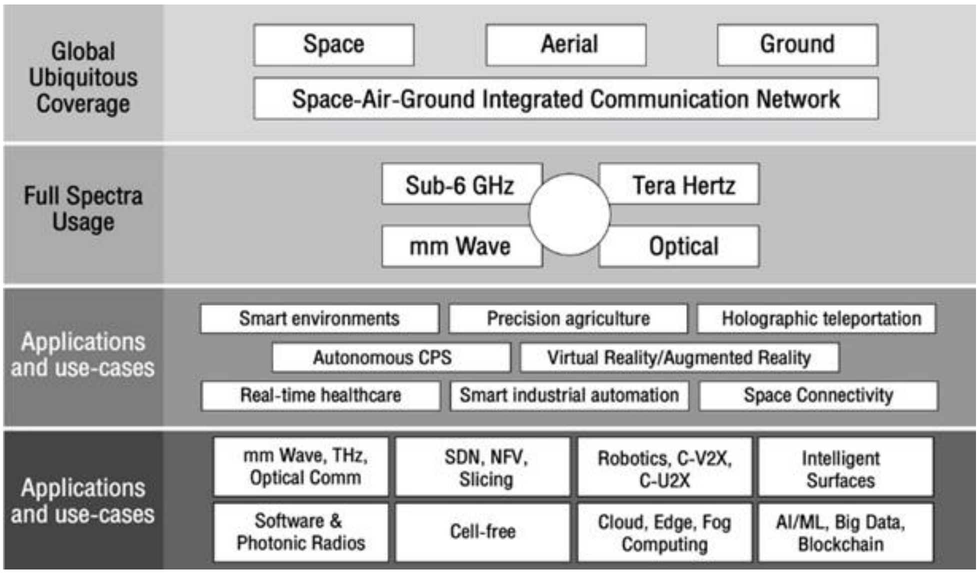

Figure 1. Drone Networking with 6G Vision [9].

Due to the continuous improvement in drone payload weight and communication device miniaturization, it becomes more practicable for drones to carry communication devices in the sky, to provide or enhance the information and communication services for the terrestrial users in the mobile networks. In future mobile networks, transmitting, receiving, and computing functions are integrated, and operating equipment provides the spatial and functional flexibility to support heterogeneous services [2]. Generally, the interaction between drones and the mobile network can be fully exploited to improve the communication performance of both drones and existing mobile users on the ground, which calls for a novel research model to investigate their linkage design and performance optimization.

This paper explores the transformative potential of mobile-enabled drone communications, focusing on their integration into terrestrial and non-terrestrial networks as a foundational step toward the Internet of Drones (IoD). Section II introduces the IoD concept within mobile network environments, addressing the need for reliable and scalable communication to support beyond visual line-of-sight (BVLOS) missions and advanced drone applications. Section III outlines the key challenges associated with drone safety, security, and Unmanned Aircraft System Traffic Management (UTM), emphasizing the importance of real-time tracking and collision avoidance mechanisms. Section IV presents the IAAI initiative project, a comprehensive testbed designed to demonstrate mobile-enabled drone systems under real-world conditions, integrating emerging wireless standards such as 5G, B5G, and pre-6G technologies. Section V provides experimental results demonstrating the feasibility of achieving high uplink throughput, low latency, and robust connectivity, alongside interference mitigation strategies in challenging operational environments. Section VI discusses the implications of these findings, identifying opportunities for optimization and future innovation in drone communication systems. Finally, Section VII concludes the paper by highlighting the contributions of this research to advancing IoD ecosystems, addressing scalability, safety, and regulatory concerns, and paving the way for space-air-ground integrated networks in 6G and beyond.

INTERNET OF DRONES IN THE MOBILE NETWORK ENVIRONMENT

Wide-area network coverage is needed to safely expand drone operations for beyond visual line-of-sight missions. Mobile networks can contribute secure wide-area mobile connectivity, utilizing reliable and accepted technology based on mobile licensed spectrum and global standards [4]. Nowadays, 4G and 5G networks can assist the initial deployment of low-altitude drones. The remarkably improved capabilities of 5G and beyond 5G networks will provide more efficient and effective mobile connectivity for huge drone implementations with more diversified applications. As 5G rollouts continue to gather impetus worldwide, network sophistication and site numbers will expand. Connected drones in turn can aid to expedite site deployment and rollout while diminishing health and safety hazards. To improve the 5G networks potentiality to serve drones, researchers are driving the establishment of drone-related enhancements to Release 18 of the 5G NR standard. New vision is that

NR networks will become even more advanced in serving drones compared to 4G LTE networks [1]. Guaranteeing safe and efficient operation of drones demands ultra-reliable, low-latency, and highly secure communication links between the drones and their ground control stations (GCSs), aiming to support their two-way control and non-payload communication (CNPC) [10]. Explicitly, CNPC comprises the consecutive types of information flows between the drone and GCSs, which are imperative to the UAV operation: command and control data, air traffic control (ATC) relay data [11]. To make the Internet of Drone a reality, the large-scale deployment of drones requires reliable and secure wireless communications that ensure safe control and operation of drones. This will require proficient system design for wireless communication, intelligent computation, and reliable control systems. However, the existing mobile communication technology is basically optimized for serving user equipments (UEs) located on the ground. On this matter, the efficient support of aerial UEs, particularly in the next generation wireless networks which need to provide seamless connectivity, faces new challenges due to their relatively high altitude, mobility, massive deployment, and flight safety requirements. Subsequently, the design of mobile-connected drone systems for assisting aerial UEs has received serious attention in both scholar and industry [12].

Technically, the mobile-connected drones suffer from strong interference in downlink between base stations (BSs) and drones [13]. Likewise, the uplink interference can be critical when the number of transmitting drones is massive. This, in turn, makes it challenging to provide reliable connectivity in the sky. This strong drone-ground interference issue, if not approached appropriately, could significantly restrict the performance of drone communication and even greatly reduce the performance of existing terrestrial communication, therefore leading to a spectral efficiency loss for the mobile network. To conquer this issue, new and effective interference management techniques need to be promoted.

To achieve the above intention, a promising advance is mobile-enabled drone communication, as illustrated in Fig. 2 [11], where GBSs in the existing 4G LTE or the forthcoming 5G and 6G mobile networks are applied to support communications between drones and their compatible GCSs/end users. Mobile-enabled drone communication is supposed to achieve outstanding enhanced performance over the existing point-to-point drone-ground communications, in the matter of various performance metrics such as reliability, security, coverage and data capacity. Moreover, with the high-capacity and ubiquitous mobile connectivity, drones are able to communicate with potentially ultra-high speed links to end users that are even thousands of kilometers away, thus unlocking numerous new capabilities and applications for drones in the future.

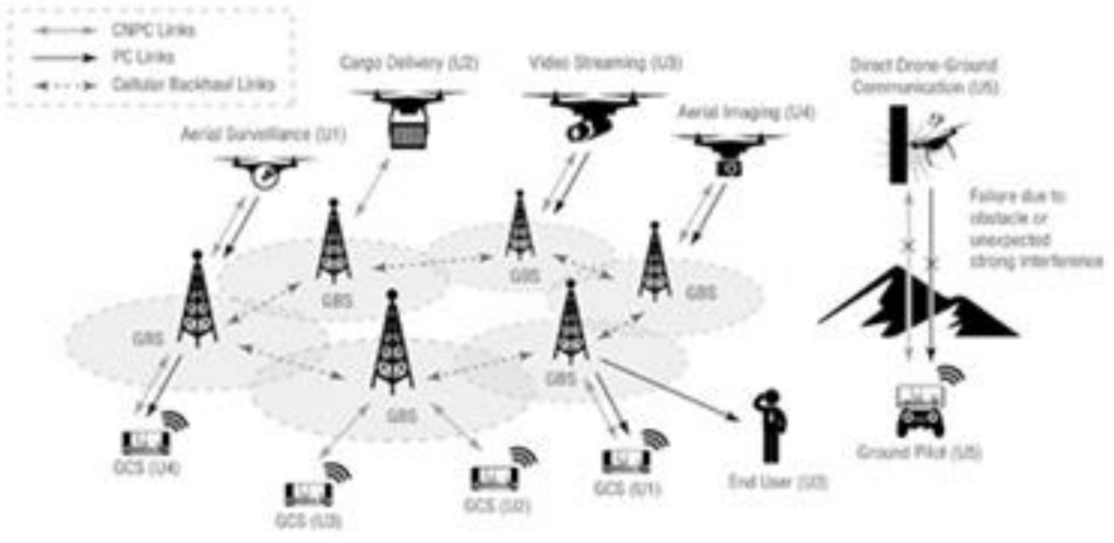

Figure 2. Mobile-enabled drone communication (where drones serve as aerial users) [11]

Despite its promising future, various technical challenges need to be overcome to achieve effective mobile-enabled drone communication, due to the significantly different characteristics between new aerial users and conventional terrestrial users. Specifically, the most notable features of drone-ground communication such as asymmetric uplink and downlink communication requirements which is different from the current mobile network, which is primarily designed to satisfy the dominant downlink data demand for downloading applications. Mobile-enabled drone communication needs to support higher data rate in the uplink (Drones-to-GBSs) for the drones to upload their mission related data to the GBSs. On the other hand, the downlink (GBSs-to-Drones) typically has much lower rate demand than the uplink, but more rigorous delay and reliability requirements in general [14].

Advancing in another type of mobile drone communications, drone-assisted mobile communication or drone-assisted mobile communication which drones operate as new aerial communication platforms to serve the terrestrial users in the mobile network. Besides enhancing the communication performance of drones by leveraging mobile-enabled drone communication, integration of drones into the network can also be exploited to enhance the quality-of-service (QoS) of the existing terrestrial mobile users, by deploying drones as new aerial communication platforms to assist in the terrestrial cellular communications [15]. Conventional terrestrial communication infrastructures are generally stationary, thus they can be designed only based on the long-term data traffic and user distribution. On the contrary, drones can be adaptably implemented as quasi-stationary aerial BSs/relays whose locations can be dynamically improved in the manner of the real-time requirement, which enables rapid network reconfiguration based on the temporal data traffic/user locations and consequently leads to enhanced performance. Basically, the high flexibility and on-demand deployment of drones make them an attractive solution to provide ubiquitous mobile coverage for remote areas or specific events, without the requirement of building new terrestrial communication infrastructure.

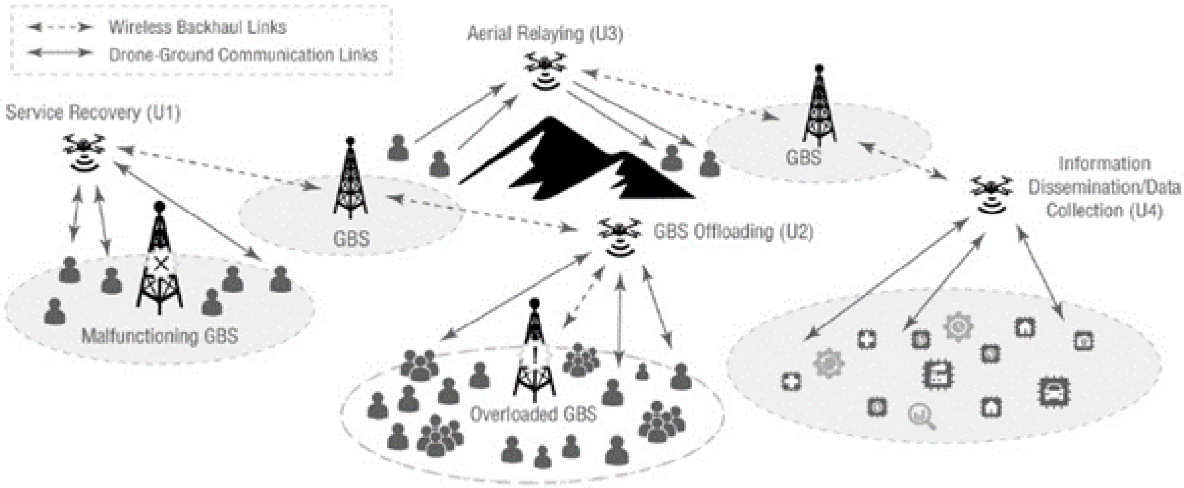

Figure 3. Drone-assisted cellular communication (where drones serve as aerial communication platforms) [15]

Drone-assisted mobile communication is proposed to be an important technology for future mobile networks to satisfy the more dynamic and diversified communication demands. Some typical use cases include: cellular coverage expansion in remote areas without ground communication infrastructure; abrupt service recovery when the ground communication infrastructure is malfunctioning due to natural disasters in emergency responses; aerial relaying between distant ground user clusters; and cost-effective data management and data collection for Internet of Things (IoT) and machine-type communications (MTC) [15], which are illustrated in Fig. 3.

To realize the promising vision of drone-assisted cellular communication, the 3D deployment for quasi-stationary drone communication platforms is more challenging than ever in the conventional 2D placement of GBSs/ relays, due to the extra design in the drone altitude, as well as the more flexible horizontal deployment of the drone in the absence of ground obstacles. Moreover, the dynamic drone deployment to furnish for the change of ground network topology is also a major design problem. Essentially, due to the lack of wired backhauls which are a reliable connection for the GBSs/relays, drone communication platforms need to rely on wireless backhauls to connect to the GBSs/gateways. Besides the conventional communication-related energy consumption due to signal processing and amplification, drone communication platforms are subjected to the additional propulsion energy consumption for them to remain float and move freely [16]. Unlike ground communication infrastructures which usually have plenty of power supply, energy-efficient design is crucial for strengthening the long-term performance and operation of drone-assisted mobile communication.

CHALLENGES IN SAFETY, SECURITY, AND TRAFFIC MANAGEMENT

Rapid advancement in the development and use of unmanned aerial systems has seen an increase in threats and sabotage. This has the potential to disrupt essential systems that rely on drones for various operations. Protection of citizens and infrastructure from any drone activity may be compromised if control and monitoring operations are not efficient. The advancement and use of drone technology also come with the need to provide services and tools that meet the requirements for air traffic management. The drive to allow drone operations by service providers in various applications has seen an increase in the number of low-cost drones used. This has called for new challenges such as safety, privacy, airspace integration, security, and the need for the capability to control the drones from service providers and national security agencies.

In the safety aspect of drones, a key requirement for aircraft has always been that the pilot is in control of the aircraft continuously at all times. When the pilot is not onboard, then the reliability of the communications link between the pilot and the drone becomes critical. Safe operation must also consider the need to operate in challenging or adversarial environments where drones may be faced with attacks such as electromagnetic interference (EMI) or jamming [2]. 3GPP systems provide multiple quality of service (QoS) classes to meet the requirements. Many researchers have taken the approach of introducing onboard intelligence in their drones to allow them to avoid collisions and perform basic operations while satisfying QoS requirements. Some research works introduce multiple technologies such as mobile cellular or satellite to reserve redundancy.

Drones are helpful in raising efficiency in everyday life. With the number of drones transforming drones into the Internet of drones will help enhance the safety and performance of the drone communication. However, privacy, security, and communications are still a huge concern of the governments or regulators. To handle the security problem issues, a key step in enforcing proper use of drones is to be able to identify drones. Like any vehicle in any country, drones must be registered and the registration ID must be on the body of the drone [17]. Moreover, the regulator should support Remote ID. The form of Remote ID currently required is a periodic broadcast beacon transmitted over WiFi or Bluetooth. These can be received by an appropriately configured smartphone. This solution has limitations since the broadcast is on unlicensed bands, it is not clear that it will be sufficiently reliable in congested urban environments. It also requires that a person be present near the drone with an appropriate device to receive the broadcast. To overcome the limitation, a new form of Remote ID was developed. This is a mobile network-based remote ID where the drone periodically transmits its location and status to a remote database. That database can then be queried to find what drones are in an area and associated information such as who owns the drone and its mission. That solution, however, relies on having a regulator to manage databases to handle this and other related queries [2].

In terms of airspace control, there are extensive procedures governing their operations as well as flight plans within the airspace. The aviation community is understandably concerned with having large numbers of drones flying around without robust tracking of where they are. However, due to the sheer number of drones, this process needs to be automated. The system handling drone air traffic management is referred to as the Unmanned Aircraft System Traffic Management (UTM). Mobile networks can enable reliable connectivity between the drone and its controller and UTM can connect to the drone and the drone controller through the core network and the radio access network.

PRACTICAL PROJECT INITIATIVE AT IAAI: MOBILE-ENABLED INTERNET OF DRONES TESTBED

To advance research on mobile-enabled UAV communications and implement the Internet of Drones (IoD) concept, a comprehensive testbed project is proposed at the International Academy of Aviation Industry (IAAI), King Mongkut's Institute of Technology Ladkrabang (KMITL). This testbed will function as a living laboratory for the development, validation, and deployment of UAV communication systems integrated with both terrestrial and non-terrestrial mobile networks. The outcomes are designed to support academic research, foster industry innovation, and enable real-world applications.

A. Project Objectives

The core objectives of this project are as follows:

1. Testbed Development: Establish an operational test environment to evaluate mobile-enabled drone communication technologies under diverse real-world conditions.
2. Integration of Emerging Wireless Standards: Investigate and demonstrate 5G, Beyond 5G (B5G), and pre-6G network capabilities, such as ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC).
3. Drone-Assisted Communication Trials: Implement drone-assisted communication for use cases such as remote coverage extension, disaster response, and IoT data aggregation.
4. Enhanced Traffic Management and Safety: Test advanced Unmanned Aircraft System Traffic Management (UTM) solutions integrated with mobile networks for real-time drone identification, tracking, and collision avoidance.
5. Industry Collaboration: Partner with mobile network operators, drone manufacturers, and regulators to align with practical and regulatory requirements.

Place figures and tables at the top and bottom of columns. Avoid placing them in the middle of columns. Large figures and tables may span across both columns. Figure captions should be below the figures; table heads should appear above the tables. Insert figures and tables after they are cited in the text. Use the abbreviation "Fig. 1", even at the beginning of a sentence.

B. Methodology

The methodology for this research project involves a real-world experimentation. The following phases outline the approach:

1. Needs Identification and System Design

The initial phase focuses on identifying the specific needs and requirements for mobile-enabled IoD systems. Stakeholder engagement, including consultations with regulators, industry experts, and academia, is conducted to define key performance indicators (KPIs) such as communication latency, throughput, and reliability. Design requirements for hardware (drone platforms, base stations, and sensors) and software (protocol stack, data processing modules, and UTM integration) are determined.

2. Testbed Setup and Hardware Configuration

The establishment of the mobile-enabled Internet of Drones (IoD) testbed at the International Academy of Aviation Industry (IAAI), King Mongkut's Institute of Technology Ladkrabang (KMITL), involves a structured setup process to facilitate controlled experiments and real-world validation of drone communication systems. This outlines the detailed process of testbed configuration, hardware deployment, and integration with terrestrial and non-terrestrial mobile networks.

2.1 Site Selection and Environmental Preparation

The testbed site at IAAI is selected for its open-air accessibility and controlled infrastructure to support diverse flight experiments. The preparation includes:

- Site Mapping: Geographical mapping of the test area to define flight zones, no-fly zones, and observation stations.
- Flight Corridor Design: Predefined corridors are set up for Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) testing at varying altitudes (50m to 300m) and distances.
- Safety Protocols: Installation of protective barriers, emergency control measures, and designated take-off/landing zones to ensure operational safety.

2.2 Hardware Configuration

The testbed incorporates the following hardware components to establish a robust drone communication network:

1. Drones: Commercial off-the-shelf (COTS) drones modified with advanced communication modules and sensors to support mobile-enabled IoD functionality:

- Communication Modules: 4G/5G radio modules integrated with Software-Defined Radio (SDR) systems to adapt frequency bands and network parameters dynamically.
- Sensors: GPS, altimeters, and IMUs (Inertial Measurement Units) for flight stability, trajectory measurement, and real-time positioning.
- Power Systems: Extended battery packs to enable prolonged flight times, with an average flight duration of 40-60 minutes.

2. Mobile Base Stations: Portable 4G LTE and 5G base stations deployed within the testbed environment to provide real-time connectivity. The specifications include:

- Frequency Bands: Configurable across licensed spectrum bands.
- Coverage Radius: Up to 2 km per station, ensuring connectivity for mid-altitude and long-range flights.
- Network Core Integration: Connectivity to a core network system for managing drone data flow, handovers, and real-time traffic control.

3. Ground Control Systems (GCS): Ground stations equipped with communication antennas and control software for real-time drone operation and monitoring:

- Control Interface: Software tools for issuing flight commands, monitoring telemetry data, and ensuring system safety.
- Data Processing Units: Edge-computing systems to process uplinked data, such as video streams, sensor readings, and control inputs.

4. Monitoring Equipment: Additional devices include high-definition cameras, spectrum analyzers, and signal monitoring tools:

- Cameras: Deployed around the test site to visually track drone movements and validate flight trajectories.
- Spectrum Analyzers: Used to measure signal quality, interference levels, and frequency utilization in the test environment.

2.3 Network Integration

The testbed integrates drones and ground systems with existing mobile networks to validate communication capabilities:

- 5G Network Core: A private 5G network is established to provide ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC).
- IP Configuration: Each drone and base station is assigned a unique IP address for data routing and remote control.
- Handover Mechanisms: Real-time handovers between base stations are tested to maintain connectivity during drone mobility.

2.4 Software Infrastructure

The software infrastructure includes tools for real-time communication, system monitoring, and data processing:

- Protocol Stack: Implementation of 5G NR protocol stacks for communication between drones and ground control systems.
- Data Logging Tools: Software for collecting telemetry data, including latency, throughput, and signal strength.
- UTM Integration: Drone traffic management software is incorporated to facilitate real-time drone tracking, collision avoidance, and Remote ID validation.

2.5 Calibration and Testing

The hardware and software components are calibrated to ensure precise operation:

- Signal Calibration: Tuning of communication modules for optimal signal strength and minimal packet loss.
- Flight Path Validation: Preflight testing with controlled routes to validate hardware stability and software performance.
- Interference Baseline Measurements: Assessing baseline interference in urban and rural

scenarios for comparison with experimental results.

2.6 Iterative Setup Optimization

Initial field trials are conducted to identify challenges such as signal interference, environmental degradation, and hardware limitations. Findings from these trials inform iterative improvements to the testbed setup, including:

- Adjusting drone communication parameters (e.g., transmission power, frequency band selection).
- Optimizing base station placement to enhance coverage and minimize dead zones.
- Implementing advanced interference mitigation techniques such as beamforming and frequency reuse.

3. Experimental Design and Data Collection

The experimental phase involves systematic trials under controlled and dynamic conditions, with drones performing predefined trajectories to collect communication and performance data. The following experimental parameters are measured:

- Uplink/Downlink Throughput: Evaluating the data rate between drones and base stations.
- Latency: Measuring transmission delay under varying flight altitudes and mobility.
- Signal Reliability: Analyzing packet loss and SNR under LoS/NLoS scenarios.
- Interference Management: Evaluating the impact of noise and overlapping signals in urban and rural environments.

Quantitative data collection is supplemented with direct observation, video recordings, and in-depth interviews with stakeholders to assess system performance and practical feasibility.

4. Wireless Standards Integration and Validation

The project integrates emerging wireless standards such as 5G, B5G, and pre-6G within the testbed. Real-world experiments validate network resilience under harsh environmental conditions (rain, mist, and high winds). Focus is placed on maintaining ultra-reliable low-latency connections for drone operations while complying with local regulatory standards on spectrum usage and network integration.

The experimental validation emphasizes interoperability with existing mobile networks and explores solutions to extend coverage and communication range. Emphasis is placed on ensuring compliance with national telecommunications regulations and obtaining necessary permissions for drone flight operations.

C. Contributions to the Research Community

This project will make the following key contributions to advancing drone communication research:

1. Benchmarking Communication Performance: Evaluate key metrics such as latency, throughput, and reliability under real-world conditions, with datasets made publicly available for academic research.

2. Development of 6G-Compatible IoD Solutions: Explore space-air-ground integrated networks, laying the foundation for future 6G research in heterogeneous communication environments.
3. Advancement of UTM Solutions: Test practical implementations of Remote ID and real-time drone tracking systems, contributing to regulatory compliance and safety in drone airspace management.
4. Cross-Disciplinary Collaboration: Facilitate innovation by integrating expertise from wireless communication, drone design, AI, and aerospace engineering.

D. Future Prospects and Scalability

The outcomes of this testbed project will provide a platform for scaling IoD solutions to broader applications. Future directions include:

- Development of Smart Airspace Solutions: Designing large-scale UTM systems for efficient and safe drone operations.
- Regulatory Framework Proposals: Informing evidence-based policies for drone operations in Thailand and internationally.
- Commercial Applications: Supporting Drone-as-a-Service (DaaS) models for logistics, precision agriculture, and disaster recovery.

RESULTS

The experiments focused on evaluating uplink/downlink throughput, latency, signal reliability, and interference management under diverse environmental and operational conditions.

A. Uplink and Downlink Throughput

The experiments revealed significant differences in throughput performance under Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions:

Line-of-Sight (LoS) Results: Uplink Throughput: Achieved an average of 95 Mbps in low-altitude flights (50–100 meters) and 85 Mbps in mid-altitude flights (200–300 meters).

Downlink Throughput: Maintained stable performance with an average of 70 Mbps across all test altitudes.

Non-Line-of-Sight (NLoS) Results: Uplink Throughput: Decreased by approximately 35%, averaging 60 Mbps due to signal attenuation caused by obstacles and interference.

Downlink Throughput: Observed a similar drop, with an average of 45 Mbps in obstructed environments.

The results demonstrate that mobile networks are capable of supporting high-rate data transmission for drone communication, particularly in LoS scenarios. Performance degradation under NLoS can be mitigated with optimized flight paths and interference management techniques.

B. Latency Performance

Latency was measured under varying altitudes and mobility scenarios:
Low-Altitude Flights (50–100 meters): Achieved an average latency of 20 ms, meeting the requirements for ultra-reliable low-latency communication (URLLC).
Mid-Altitude Flights (200–300 meters): Latency increased slightly to 35 ms due to signal propagation delay and interference.
Dynamic Mobility Scenarios: Experiments with drones moving at 10–20 m/s showed latency peaks of up to 50 ms when transitioning between base stations. However, handover mechanisms in 5G networks reduced packet drops to less than 1%.
These findings confirm that 5G networks can effectively support real-time drone control and data transmission, even under high mobility and dynamic conditions.

C. Signal Reliability and Packet Loss

Signal reliability was analyzed using Signal-to-Noise Ratio (SNR) and packet loss under LoS and NLoS scenarios:
Signal-to-Noise Ratio (SNR): LoS environments maintained an average SNR of 25 dB, ensuring high-quality communication. NLoS environments experienced a drop to 15 dB, especially in urban areas with dense interference.
Packet Loss: Under LoS, packet loss remained minimal (< 0.5%).
In NLoS conditions, packet loss increased to 2–3% but remained within acceptable thresholds for real-time communication.
The results highlight the need for advanced interference mitigation techniques in urban deployments to improve SNR and reduce packet loss.

D. Interference Management

Interference was evaluated in scenarios with multiple drones and ground base stations:
Uplink Interference: Measured significant uplink interference in urban areas where drone density exceeded 10 drones/km^2. Power control and frequency reuse schemes effectively reduced interference levels by 40%.
Downlink Interference: Downlink interference remained minimal, with no significant impact observed on terrestrial users.
These findings underscore the importance of spectrum management and advanced interference cancellation techniques to ensure reliable drone-ground communication.

E. Environmental Impact on Communication Performance

Field trials under adverse environmental conditions (rain, wind, and fog) revealed the following:
Rain and Fog: Data throughput and SNR dropped by 10–15%, particularly in mid-altitude flights. However, communication remained stable, with no critical signal loss.
High Winds: Propulsion energy consumption increased by 20%, but communication latency and reliability were not significantly affected.
These results demonstrate that 5G and beyond-5G networks can maintain robust drone communication even under challenging weather conditions.

F. Integration with Traffic Management Systems (UTM)

Integration of the testbed with Unmanned Aircraft System Traffic Management (UTM) systems enabled:
Real-Time Tracking and Collision Avoidance: Achieved real-time drone identification and tracking accuracy of 98%, even under high-density scenarios. Collision avoidance mechanisms performed efficiently, ensuring safe drone operations.
Remote ID Functionality: Successfully validated mobile network-based remote ID, with minimal latency in transmitting drone location and status data.

G. Summary of Key Results

Table 1 presents a comparative analysis of key performance metrics for mobile-enabled drone communication under Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions. The table highlights differences in uplink and downlink throughput, latency, signal-to-noise ratio (SNR), packet loss, and real-time Unmanned Aircraft System Traffic Management (UTM) tracking accuracy. The results demonstrate that while LoS conditions provide higher uplink and downlink throughput (95 Mbps and 70 Mbps, respectively), NLoS environments experience significant performance degradation, particularly in urban areas, where uplink throughput drops to 60 Mbps and downlink throughput to 45 Mbps due to signal attenuation and interference. Similarly, latency increases from 20-35 ms in LoS scenarios to 35-50 ms in NLoS cases, affecting real-time communication reliability. The SNR also exhibits a decline from 25 dB to 15 dB in NLoS environments, leading to increased packet loss (2-3%) compared to LoS conditions (<0.5%). Despite these challenges, real-time UTM tracking accuracy remains robust at 98% in LoS and 95% in NLoS conditions, indicating the effectiveness of mobile-enabled drone communication for collision avoidance and air traffic management.

Table 1. A comparative analysis of key performance metrics for mobile-enabled drone communication

Metric	**LoS Performance**	**NLOS Performance**	**Remarks**
Uplink Throughput	95 Mbps	60 Mbps	Higher drop in urban NLOS
Downlink Throughput	70 Mbps	45 Mbps	Stable in LoS conditions
Latency	20-35 ms	35-50 ms	Higher during handovers
Signal-to-Noise Ratio (SNR)	25 dB	15 dB	Reduced by environmental factors
Packet Loss	<0.5%	2-3%	Higher in urban NLOS
Real-Time UTM Tracking Accuracy	98%	95%	Effective for collision avoidance

DISCUSSION

The experimental results derived from the mobile-enabled Internet of Drones (IoD) testbed highlight both the technical feasibility and the inherent challenges of integrating drones into 5G and beyond mobile networks. This section provides a deeper technical interpretation of the results, identifies key performance limitations, and outlines future optimizations required for large-scale deployments of drones within terrestrial and non-terrestrial networks.

A. Throughput Performance Analysis

The results demonstrated that uplink throughput outperformed the downlink, particularly under LoS conditions. This asymmetry aligns with the nature of drone-ground communication, where the demand for uplink capacity (drones sending data to base stations) is higher than for downlink data flows.

1. Technical Factors Influencing Throughput

- High-Angle Interference: Drones at elevated altitudes receive strong signals from multiple ground base stations (GBSs) due to the absence of obstacles, causing co-channel interference. This phenomenon, observed in NLoS environments, resulted in a 35% drop in uplink throughput.

- Antenna Design and Beamforming: Ground base stations are typically designed with downward-tilted antennas to serve terrestrial users, reducing signal strength for aerial drones. The testbed highlighted the importance of utilizing advanced 3D beamforming and multi-antenna systems (e.g., Massive MIMO) to dynamically adjust signal directionality.
- Frequency Reuse and Spectrum Management: The overlap of frequencies between terrestrial and aerial users necessitates frequency reuse planning and interference-aware scheduling algorithms to maximize spectral efficiency.

2. Optimizations for Future Deployments

- Implement uplink power control techniques to manage interference caused by dense drone networks.
- Deploy directional antennas and beam tracking algorithms to enhance the drone-GBS link robustness in high-altitude deployments.

B. Latency Analysis and Mobility Impact

The testbed results demonstrated latency ranging between 20 ms and 50 ms, with the upper bound observed during drone handovers across multiple base stations. Latency performance is critical for drone applications requiring real-time control and ultra-reliable low-latency communication (URLLC), such as collision avoidance, video streaming, and time-sensitive operations.

1. Handover Delays

- Frequent Cell Switching: Due to their altitude and mobility, drones often traverse multiple cells, triggering frequent handovers. Delays arise primarily from control signaling overhead and the time required for re-establishing connections.
- Seamless Handover Mechanisms: The experimental phase underscored the need for inter-cell coordination and predictive algorithms leveraging Machine Learning (ML) to pre-allocate resources and minimize handover latency.

2. Latency under Dynamic Mobility

- While low-altitude flights maintained low latency, drones in mid-to-high altitudes exhibited propagation delays due to larger transmission distances and weaker signal strengths.
- Integrating edge computing solutions into drone-GBS communication systems can significantly reduce latency by offloading computational tasks closer to the network edge, improving response time for drone control and data processing.

3. Future Focus

- Implement make-before-break handover techniques (used in 5G networks) to preemptively establish new connections before breaking the old one.
- Explore the deployment of non-terrestrial networks (NTNs), including low earth orbit (LEO) satellites, to ensure ubiquitous coverage and ultra-low latency in remote or high-altitude scenarios.

C. Signal Reliability and Interference Management

The signal reliability, measured via Signal-to-Noise Ratio (SNR), demonstrated a significant drop in NLoS environments and high-interference urban settings.

1. Technical Sources of Interference

- Uplink Interference: Due to drones transmitting at higher power to compensate for altitude, uplink interference with neighboring base stations is exacerbated, particularly in drone-dense environments.
- Downlink Interference: Drones receive overlapping signals from multiple base stations due to their elevated vantage points, a phenomenon known as "near-far" interference.
- The experimental findings highlight the need for advanced interference management strategies, such as:
  - Interference Cancellation Techniques: Leveraging advanced Successive Interference Cancellation (SIC) algorithms to separate strong and weak signals at the receiver.
  - Directional Beamforming: Applying adaptive beamforming at drones to minimize noise and focus on desired signal paths.
  - Power Control Policies: Dynamic power control across drone transmitters to mitigate uplink interference with terrestrial users.

2. Optimized UAV Placement

- For drone-assisted communication (serving as aerial base stations or relays), the 3D placement optimization of drones (altitude and position) plays a critical role in mitigating interference and maximizing coverage.

D. Environmental Challenges

Field experiments under adverse weather conditions, such as rain, fog, and wind, highlighted their impact on signal quality and system performance:

1. Rain and Fog Attenuation

- High-frequency signals used in 5G millimeter-wave bands (mmWave) are particularly susceptible to attenuation caused by rain and atmospheric particles.
- To counter this issue, hybrid frequency bands (e.g., combining sub-6 GHz and mmWave) can be employed, ensuring reliable connectivity under varying weather conditions.

2. High Winds and Energy Consumption

- Drones require additional propulsion energy to stabilize and maintain flight in high-wind scenarios, directly impacting the operational endurance of drone platforms.
- Future solutions could include energy-efficient path optimization algorithms and the integration of solar-powered drones for extended operation.

E. Integration with Unmanned Aircraft System Traffic Management (UTM)

The successful integration of UTM systems with mobile networks in the testbed demonstrated the feasibility of achieving real-time drone tracking, identification, and collision avoidance:

1. Real-Time UTM Capabilities

- Mobile-based Remote ID systems showed high reliability in urban and rural settings, overcoming the limitations of Wi-Fi/Bluetooth-based solutions.
- Real-time data sharing between drones and UTM systems ensured timely collision avoidance, even in high-density drone operations.

2. Challenges in Scalability

- As drone density increases, UTM systems must efficiently handle massive data streams for real-time coordination and identification. This highlights the need for scalable network architectures and AI-driven traffic optimization algorithms.

CONCLUSION

This paper presents comprehensive exploration of mobile-enabled drone communication as a foundational technology for realizing the Internet of Drones (IoD). The study highlights the integration of terrestrial and non-terrestrial networks to support the safe, reliable, and scalable deployment of drones, a crucial step toward the development of beyond 5G (B5G) and 6G wireless ecosystems. By leveraging advanced mobile network features—such as ultra-reliable low-latency communication (URLLC) and massive machine-type communication (mMTC)—we emphasize that mobile networks are well suited to address the unique requirements of drone operations, including high mobility, asymmetric data flows, and real-time traffic management.

The IAAI initiative project proposed in this paper serves as a practical testbed to demonstrate these concepts in real-world conditions. The project highlights the potential of drones to act both as aerial communication users and as communication platforms supporting terrestrial users. This dual role unlocks numerous applications, such as disaster response, IoT data aggregation, logistics, and remote coverage extension, while advancing the research and deployment of drones within modern mobile networks.

The study also highlights the importance of space-air-ground integrated networks as a foundational element of future 6G systems, enabling seamless connectivity across terrestrial, aerial, and satellite environments. Additionally, the research demonstrates the practical implementation of Unmanned Aircraft System Traffic Management (UTM) solutions to ensure real-time drone identification, tracking, and airspace safety. Furthermore, mobile-enabled drone communications unlock emerging applications such as precision agriculture, surveillance, emergency services, and smart infrastructure, meeting the growing demand for drone-based solutions across various industries. This research also identifies and addresses key challenges in safety, security, and interference management. Drones must operate reliably in harsh and dynamic environments while maintaining ultra-secure communication links and complying with regulatory standards. The development of mobile-based Remote ID systems and advanced UTM frameworks further strengthens drone operations, ensuring scalability and integration into shared airspace.

Looking ahead, this work lays the foundation for future research and innovation in IoD systems. The outcomes of the IAAI initiative project provide insights into the practical deployment of drones within mobile networks, serving as a reference for policymakers, network operators, and drone manufacturers. As B5G and 6G technologies continue to evolve, the convergence of drones, ground, and satellite networks will lead to seamless, space-air-ground integrated communications, enabling a globally connected and intelligent IoD ecosystem.

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REFERENCES

[1]. Ericsson, “The sky is not the limit: The past, present, and future of the Internet of Drones,” 2021.

[2]. Mohammad Mozaffari, Xingqin Lin, and Stephen Hayes, “Towards 6G with Connected Sky: UAVs and Beyond,” 2021.

[3]. Zulkifley, M. A., Behjati, M., Nordin, R., & Zakaria, M. S. (2021). Mobile Network Performance and Technical Feasibility of LTE-Powered Unmanned Aerial Vehicle. *Sensors (Basel, Switzerland)*, *21*(8), 2848. https://doi.org/10.3390/s21082848

[4]. X. Lin *et al.*, "The Sky Is Not the Limit: LTE for Unmanned Aerial Vehicles," in *IEEE Communications Magazine*, vol. 56, no. 4, pp. 204-210, April 2018, doi: 10.1109/MCOM.2018.1700643.

[5]. Muruganathan, S.D., Lin, X., Maattanen, H., Zou, Z., Hapsari, W.A., & Yasukawa, S. (2021). An Overview of 3GPP Release-15 Study on Enhanced LTE Support for Connected Drones. *IEEE Communications Standards Magazine, 5*, 140-146.

[6]. K. P. Valavanis and G. J. Vachtsevanos, Handbook of Unmanned Aerial Vehicles. Springer, 2014.

[7]. R. Austin, Unmanned Aircraft Systems: UAVS Design, Development and Deployment. John Wiley & Sons, 2011.

[8]. X. Lin, R. Wiren, S. Euler, A. Sadam, H.-L. Ma¨att ¨ anen, S. Muru- ¨ ganathan, S. Gao, Y.-P. E. Wang, J. Kauppi, Z. Zou et al., "Mobile network-connected drones: Field trials, simulations, and design insights," IEEE Vehicular Technology Magazine, vol. 14, no. 3, pp. 115–125, Sept. 2019.

[9]. Debashisha Mishra, Anna Vegni, Valeria Loscri, Enrico Natalizio. Drone Networking in 6G Era - A Technology Overview. IEEE Communications Standards Magazine, Institute of Electrical and Electronics Engineers, 2022.

[10]. ITU, "Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in nonsegregated airspace," Dec. 2009, Tech. Rep. M. 2171.

[11]. S. Zhang, Y. Zeng and R. Zhang, "Cellular-Enabled UAV Communication: A Connectivity-Constrained Trajectory Optimization Perspective," in *IEEE Transactions on Communications*, vol. 67, no. 3, pp. 2580-2604, March 2019, doi: 10.1109/TCOMM.2018.2880468.

[12]. 3GPP TR 36.777, "Enhanced LTE support for aerial vehicles," Dec. 2017.

[13]. Mei, Weidong & Wu, Qingqing & Zhang, Rui. (2019). Cellular-Connected UAV: Uplink Association, Power Control and Interference Coordination. IEEE Transactions on Wireless Communications. 18. 5380-5393. 10.1109/TWC.2019.2936021.

[14]. R. J. Kerczewski and J. H. Griner, "Control and non-payload communications links for integrated unmanned aircraft operations," 2012, NASA.

[15]. Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," IEEE Commun. Mag., vol. 54, no. 5, pp. 36–42, May 2016.

[16]. Y. Zeng and R. Zhang, "Energy-efficient UAV communication with trajectory optimization," IEEE Trans. Wireless Commun., vol. 16, no. 6, pp. 3747–3760, Jun. 2017.

[17]. Yaacoub, J. P., Noura, H., Salman, O., & Chehab, A. (2020). Security analysis of drones systems: Attacks, limitations, and recommendations. *Internet of Things*, *11*, 100218. https://doi.org/10.1016/j.iot.2020.100218