

Towards 6G UAV Networks: Experimental Performance Analysis

Anirudh Warriar

Cranfield University, United Kingdom
anirudh.warrior@cranfield.ac.uk

Saba Al-Rubaye

Cranfield University, United Kingdom
s.alrubaye@cranfield.ac.uk

Antonios Tsourdos

Cranfield University, United Kingdom
a.tsourdos@cranfield.ac.uk

Abstract—Unmanned Aerial Vehicles (UAVs) are becoming increasingly prevalent across industries, from surveillance to delivery services, necessitating seamless handover between base stations for continuous operation and safety. Challenges arise due to the need to maintain connectivity and control as the UAV transitions between different access technologies, for Fifth Generation (5G) and beyond such as Sixth Generation (6G). Factors like altitude, mobility, and dynamic operation patterns pose hurdles to achieving smooth handovers critical for mission success. Traditional strategies often lack adaptability and efficiency, prompting the exploration of innovative approaches. To address these challenges, an experimental flight trial evaluates UAV handover performance in a heterogeneous network environment compared to simulation-level analysis. The trial involves UAV flight in an urban area with non-standalone (NSA) 6G connectivity, monitoring key performance indicators (KPIs) such as reference signal received power (RSRP), signal-to-noise interference ratio (SINR), throughput, and number of handovers. The system architecture encompasses an airborne measurement platform (DJI F450 UAV with XCAL mobile measurement tool and Pixhawk 4 Autopilot) and a ground-based counterpart interfacing through the core network. The analysis focuses on three key metrics: RSRP, RSRQ, and SINR, revealing temporary interruptions attributed to the UAV's exclusive connection to the wireless network. Insights from experimental trials highlight complexities and challenges associated with UAV handover performance, informing the design of improved protocols and communication systems. By addressing these challenges, the aim is to enhance operational reliability and mission success, unlocking the full potential of UAV technology across applications like surveillance, reconnaissance, delivery services, and more.

Index Terms—Sixth Generation (6G), mobility analysis,

I. INTRODUCTION

The integration of Unmanned Aerial Vehicles (UAVs) into communication networks has opened up unprecedented possibilities across various sectors, ranging from surveillance and reconnaissance to package delivery and emergency response. In our previous work [1] different challenges and their potential solutions were discussed. One of the critical challenges in realising the full potential of UAVs lies in ensuring seamless and efficient handovers between different base stations as these aerial vehicles navigate through diverse and dynamic environments. The complexity of urban environments and the diverse applications of UAVs underscore the necessity for a reliable and efficient handover mechanism. The introduction provides an overview of the challenges associated with UAV handovers [2], [3], including the demand for increased data transfer rates, network traffic capacity, and the seamless transition between

different radio access technologies. Moreover, it establishes the importance of the experimental trial in developing solutions that enhance the mobility and connectivity of UAVs within heterogeneous networks [4], [5].

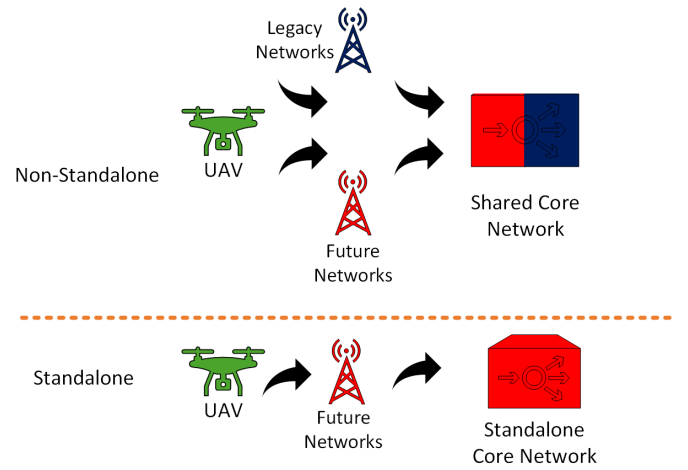


Fig. 1: Architecture for NSA and standalone operations

One of the major differences between the terrestrial user and the UAV user is that the UAV-UE can fly more freely in the third dimension. In this way, several new challenges such as coverage criteria (height- and angle-dependent channel models), handovers, and interference arose in the third dimension. The majority of existing literature focuses on simulations to assess the technical aspects of cellular-connected drones [6], [7], [8]. Few works exist on field trials and measurement campaigns to observe and examine the behaviour of the UAV-UE in real-world scenarios. This stems from the fact that such efforts are expensive, time-taking, and highly complex as they must take into account all technical aspects of a realistic deployment, while at the same time are a powerful step towards design prototyping and corroborating of the potential research problems. Available field trials vary in several aspects with respect to the deployment scenario, performance quality metric, type of radio propagation environment, test platform, aim of trial, and so on, [9], [10], [11], [11], [12], [13]. For instance, in [14], the authors presented a field measurement in a commercial LTE network. The field test encompasses the distribution and measurement

of various quality metrics such as RSRP, RSRQ, SINR and throughput with respect to the movements of the drone. Their surprising results show that the uplink throughput for drone-UE is observed to be better than the ground UE.

Research on 6G wireless networks, also known as International Mobile Telecommunications (IMT-2030), has begun. The technical name IMT-2030 follows the naming convention of previous generations, such as 5G's IMT-2020. This research is being conducted by the 5G standard development organization, the Third Generation Partnership Project (3GPP), which operates under the International Telecommunications Union (ITU). The ITU is a United Nations agency responsible for spectrum guidance, spectrum harmonization, and the promulgation of technical standards to industries and countries worldwide. IMT-2030 will be highly digitized, intelligence-driven, and data-centric, enabled by instantaneous and limitless wireless connectivity. In [15], the authors demonstrated an experimental evaluation in which the drone-UE flies close to a commercial 5G NR BS. The radio link quality, handover events, and throughput were analysed at two different heights. First, they conclude that the higher the altitude, the lower the throughput. Second, the 5G implementation used in their study does not improve uplink throughput compared to the LTE network. However, it should be noted that the reported downlink performance is biased as only one 5G BS was there. The authors assume that uplink analysis requires more investigation.

The authors in [16] performed an experimental evaluation of a drone-UE connected to an LTE-Advanced cellular network running 3GPP Release 13, which supports carrier aggregation with 2x2 MIMO. The experiment is conducted in an unobstructed field between the BS and the drone to prevent signal attenuation and reflected paths. TCP measurements show how the quality metrics depend on the flight height.

This paper, through a systematic exploration of UAV handovers in real-world scenarios, contributes to valuable insights and practical solutions to propel the integration of UAVs into communication networks, ultimately unlocking new dimensions of efficiency and capability for these unmanned systems.

II. DUAL-CONNECTIVITY IN HETEROGENEOUS 5G AND BEYOND NETWORKS

Future advanced networks, will lead to excessive capacity demands and impose a heavy burden on operators in terms of increased capital investments and operational costs. Early efforts were dedicated to heterogeneous networks, to meet these growing demands [17], [18]. In unexpected or emergency situations (such as disaster relief and service recovery), terrestrial infrastructure is economically infeasible and difficult due to high operational expenditure, as well as sophisticated and volatile environments. To address this issue,

intelligent heterogeneous architecture leveraging UAVs has been a promising new paradigm to facilitate usage scenarios of future wireless networks. Heterogeneous networks are defined as the integration of different telecommunication technologies with the aim of exploiting their additional characteristics.

Because of heterogeneous networks, users can transport connections between several APs of different types, benefiting from the best customized services depending on their preferences. Moreover, heterogeneous networks [19], [20] are an important solution to decreasing congestion in mobile networks by sharing traffic with other access technologies with higher flows. Owing to their fast and significant deployment, mobile networks consist of a set of heterogeneous systems managed by different operators and form distinct access networks [21]. Devices enabled with multiple wireless technologies enable the maintenance of seamless connectivity in highly dynamic scenarios, such as UAVs, switching from one wireless network to another using vertical HO techniques. All user connections in this heterogeneous environment should occur without interruption and without service degradation when the user changes from one network to another. In this context, mobile terminals (UAVs) are network multi-interfaces that enable them to move transparently from one system to another during communication.

Non Standalone (NSA) connectivity is a feature within 5G and beyond networks that enables concurrent connectivity to both legacy and next-generation radio access networks [22]. This functionality allows mobile devices to simultaneously leverage resources from both networks, resulting in improved data rates, extended coverage, and a seamless transition between the two technologies. The architectural differences between standalone and NSA are shown in figure 1

In a dual connectivity scenario, a UAV can establish connections with both a legacy NodeB (such as eNB) and a future NodeB (for example, gNB) concurrently. The user plane data is then intelligently distributed between these connections, facilitating efficient utilisation of both networks' resources. This feature is particularly advantageous during the initial phases of next-generation networks' deployment, where coverage may be limited, and the network aims to provide a consistent and enhanced service experience. Within the area these experiments were conducted, standalone networks has not been deployed, therefore the NSA feature is leveraged.

III. ENTROPY-WEIGHTED METHOD FOR HANDOVER DECISION

The entropy-weighted method is a technique used in decision-making, particularly in wireless communication systems like cellular networks, to optimize handover decisions between base stations (cells). Entropy is a measure of uncertainty or randomness in a system. In the context of wireless communication, it represents the diversity of signal strength measurements from neighbouring base stations. In the entropy-weighted method, the entropy of signal strength measurements from neighbouring base stations is calculated. Higher entropy indicates more diverse and uncertain signal strengths, while

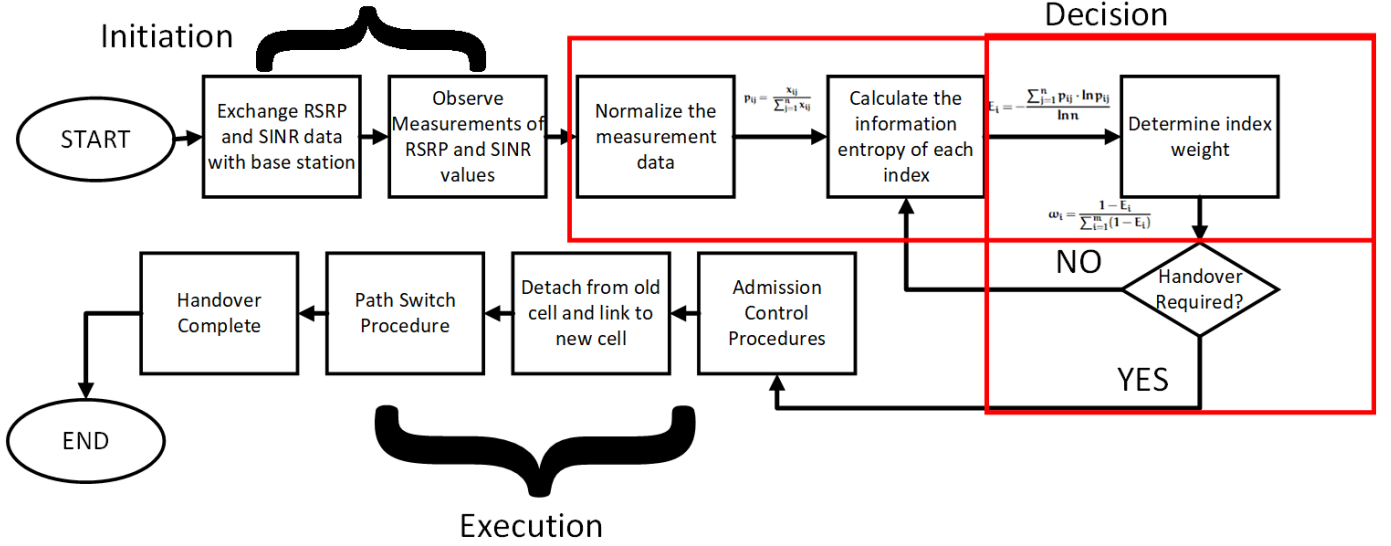


Fig. 2: Entropy Weighted Method for Handover decision-making

lower entropy indicates more consistent and predictable signal strengths.

The goal of handover decisions is to ensure seamless connectivity for UAVs as they move between different base stations. The entropy-weighted method considers both the signal strength and the diversity of neighbouring cells to make intelligent handover decisions. Entropy is calculated based on the probability distribution of signal strengths from neighbouring cells. A higher entropy indicates that the signal strengths from neighbouring cells are more evenly distributed, suggesting uncertainty about which cell to hand over to. The entropy of each neighbouring cell is weighted based on its relevance to the current cell. The weighting ensures that handover decisions are not solely based on signal strength (RSRP) but also considers signal-to-interference-plus-noise-ratio (SINR).

The following are the steps involved in the decision-making process which are also illustrated in figure 2:

- 1) Collect Signal Strength Measurements: Mobile devices continuously measure the signal strengths from neighbouring base stations.
- 2) Calculate Entropy: Entropy is calculated based on the RSRP and SINR measurements of neighbouring cells. The formula for entropy calculation involves the probability distribution of signal strengths.
- 3) Entropy Weighting: Each neighbouring cell's entropy is weighted based on its RSRP relevance. Stronger cells might have lower weights, while weaker but more diverse cells might have higher weights.
- 4) Handover Decision: The cell with the highest weighted entropy, indicating a good balance between RSRP and SINR, is selected for handover. This ensures that handover decisions are not solely based on strong RSRP but

also consider the SINR of neighboring cells.

In the evaluation of this method, m indicators and n samples are set, and the measured value of the i^{th} index in the j^{th} sample denoted as p_{ij} is calculated as follows

$$p_{ij} = \frac{x_{ij}}{\sum_{j=1}^n x_{ij}} \quad (1)$$

In the EWM, the entropy value E_i of the i^{th} index is defined as:

$$E_i = -\frac{\sum_{j=1}^n p_{ij} \cdot \ln p_{ij}}{\ln n} \quad (2)$$

In the actual evaluation using the EWM, $p_{ij} = 0$ is generally set, for the convenience of calculation. The entropy value E_i has a range of $[0, 1]$. The greater the value of E_i , the greater the degree of differentiation of index I , and thus more information can be extracted. As a result, the index should be given more weight. Consequently, in the EWM, the weight ω_i calculation method is determined by,

$$\omega_i = \frac{1 - E_i}{\sum_{i=1}^m (1 - E_i)} \quad (3)$$

IV. SYSTEM MODEL AND EXPERIMENTAL MEASUREMENT SET-UP

The aim of this trial is to analyze the key performance indicators (KPIs) of 5G networks, while performing handover during a pre-determined flight path. The system model architecture is thus, designed to facilitate airborne and ground-based network performance measurements. It integrates several components to achieve comprehensive data collection, analysis, and performance testing as shown in figure 3

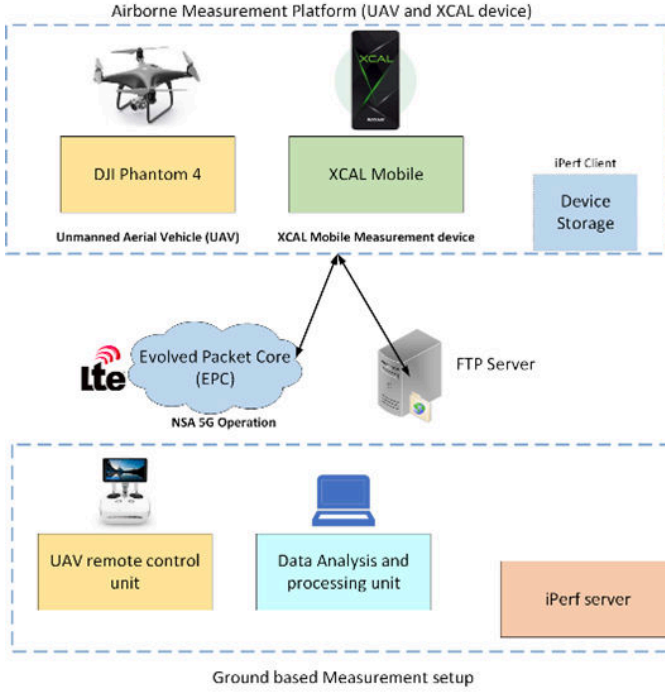


Fig. 3: System design for Measurement

A. Airborne Measurement Platform

At the core of the airborne measurement platform is a UAV. This UAV serves as the carrier for the mobile measurement tool used to gather network performance data during flights [23].



Fig. 4: Aerial Vehicle Platform for Experiment: DJI F450 Quadcopter

To conduct the proposed measurement, the exhibited DJI F450 Quadcopter in Fig. 4 was selected and built, offering a reliable and versatile platform for our purposes. The UAV system is composed of various components, each playing a crucial role in ensuring accurate and efficient data collection. The specifications and configuration of the UAV are detailed

in Table I:

TABLE I: UAV specifications

Item	Type (value)
UAV frame	DJI F450 (Quadcopter)
Motor	Brushless 2213
Radio system (Transmitter)	FS-i6X (6 channels)
Radio system (Receiver)	FS-iA6B (6 channels)
Batteries	LiPo (4200 mAh)
Maximum altitude	466 m

The Pixhawk 4 autopilot system is used as the core control unit for the UAV as shown in 5. Known for its reliability and versatility, the Pixhawk 4 is preferred for both academic and commercial applications. It serves as the bridge between the embedded sensors and the controller/simulator, facilitating seamless data exchange. Notably, open-source software (Ardupilot) is utilised to configure and calibrate the chosen UAV, providing flexibility and adaptability to meet the application requirements.

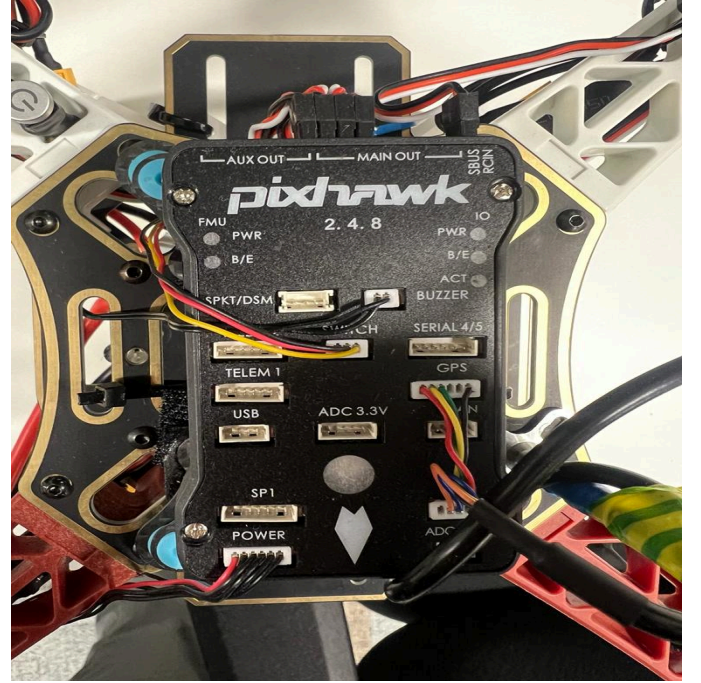


Fig. 5: Flight Control System for Aerial Vehicle platform: Pixhawk 4 Autopilot

An external GPS sensor (M8N GPS module) is paired to the autopilot to enable a high positioning accuracy of up to 50 cm with the capability to search 20 satellites per minute in open areas. This module guarantees low power consumption and enables dual compass backup. Additionally, we installed the Tf-Luna sensor, an ultrasonic lidar, in order to get better height information where GPS data is not available. This sensor provides highly accurate altitude detection up to 8 meters. A FS-iA6B transmitter of 6 channels was connected to the autopilot to increase the number of control commands using the FlySky remote controller. A LiPo battery (4200 mAh, 11.1

V) of three cells was exploited to supply power for the drone subsystems. This battery allows for a flight time of up to 18 minutes.

The XCAL Mobile device is crucial for collecting metrics such as signal strength, network speed, and connectivity stability. Data collected by the XCAL Mobile is stored in a device storage component that also functions as an iPerf client. XCAL tool is a standalone application compatible with the Android operating system (OS) and provides reliable QoS and quality-of-experience (QoE) measurements. The XCAL tool enables meticulous analysis and evaluation of QoS metrics with utmost precision. Through a comprehensive set of test scenarios, the latency, throughput, packet loss, and jitter parameters can be captured. The analysis of the acquired data entails utilizing the measurement log files generated by the XCAL tool, which are transferred to a server located at Cranfield University via the secure file transfer protocol (SFTP) to ensure secure data transmission. Subsequently, they are extracted and shown using commonly employed tools such as Microsoft Excel. For the measurement campaign, a Sony Xperia 5 II smartphone with the XCAL tool is attached to the flying platform as shown in Fig. 6

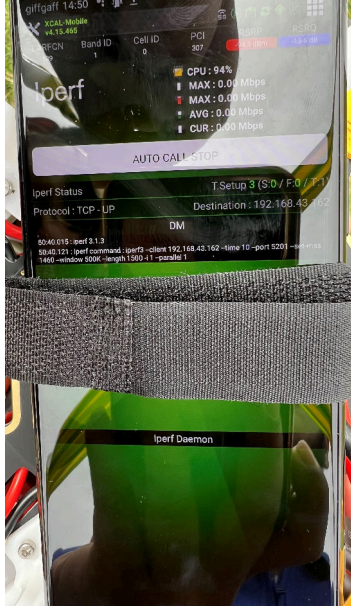


Fig. 6: Link Performance Measurement Tool: XCAL Mobile

The XCAL tool supports several scenarios for which the QoS parameters can be captured. iPerf is a network performance measurement tool that allows for the testing of bandwidth, latency, and other critical network parameters. Network performance is measured, by generating transmission control protocol (TCP) and user datagram protocol (UDP) streams between two endpoints. It supports assessing the bandwidth, throughput, and various other metrics related to network performance. Before the measurement commencement, certain characteristics were specified as:

- Destination: ATL.Speedtest.Cloudiver

- iPerf version: v 3.1.3
- Mode: UDP
- Direction: Uplink
- Packet size: 500 bytes

TABLE II: iPerf Scenario-specific Parameters

Parameter	Definition	Value
Destination	Configures IP address or URL of destination	ATL, Speedtest, Cloudiver
iPerf version	Selects v3.1.3 or v2.0.5	v3.1.3
Mode Selects	TCP or UDP	UDP
Direction	Selects Up: Transfers packet from UAV (client) to server or Down: Transfer packet from the server (client) to UAV.	UP
Packet Size	Configures iPerf buffer size to be transferred.	500 bytes

This setup enables the UAV to act as a mobile node in the network, gathering performance data from various locations and altitudes. To ensure continuous communication and data transfer, the system leverages the dual-connectivity feature. It supports both operations, providing the necessary infrastructure for the XCAL Mobile device to connect to the network. This connection is essential for real-time data transmission. Data collected by the XCAL Mobile is uploaded to an FTP server. The FTP server serves as a centralized repository for storing measurement data, allowing for efficient data management and retrieval.

B. Ground-based Measurement Setup

The data collected by the UAV is analysed and processed by a dedicated Data Analysis and Processing Unit. This unit, typically a computer equipped with specialized software, retrieves data from the FTP server. It performs detailed analysis, including signal processing, statistical analysis, and performance evaluation, to derive insights from the collected data. An integral part of the measurement setup is the iPerf server, which works in tandem with the iPerf client on the device storage. This client-server configuration facilitates comprehensive network performance testing. The iPerf tool measures various network parameters, such as throughput, jitter, and packet loss, providing a clear picture of network performance between the airborne platform and the ground-based components.

C. Communication and Data Flow

The UAV, carrying the XCAL Mobile device, collects network performance data as it flies over different areas. The data is transmitted in real-time via the core network, leveraging LTE or NSA 5G connectivity. This connectivity ensures that the data is promptly uploaded to the FTP server, where it is securely stored. From the FTP server, the data is accessed by the Data Analysis and Processing Unit on the ground. This unit processes the data to extract meaningful insights, which are then used to evaluate the network's performance. The iPerf server plays a crucial role

in validating these measurements by conducting rigorous network performance tests, ensuring the accuracy and reliability of the collected data.

This architecture provides a robust framework for airborne and ground-based network performance measurement. It integrates advanced UAV technology, mobile measurement devices, and comprehensive data analysis tools to deliver network performance insights.

V. PERFORMANCE METRICS

For the experimental trials, the handover between ground base stations need to be studied and measured. The measurements are studied based on the following performance metrics, that are standard communication metrics and specifically relevant to handover performance:

- **Reference Signal Received Power (RSRP):** RSRP is the average measure of the received power levels with respect to the power of a single signal called the reference power signal. In terms of handover, RSRP values will see slight or marked drops when switching from one base station to another.
- **Signal to Noise plus Interference Ratio (SINR):** The SINR gives a measure of how much noise and interference is present in the received signal [24]. It is expressed as a ratio of signal power and noise plus interference power. Similar to RSRP, SINR also sees variations during handover.
- **Throughput:** The throughput of a link is the average data rate of the link. The achievable throughput values of a link gives an insight into the quality of the link. The quality of the link is studied while handover is being performed.
- **Handover Count:** The number of handovers is also an important metric to study handovers. The handover count should ideally be a lower number, however, it should not compromise the quality of the link. Therefore, it is a trade-off to achieve optimal values using a handover algorithm.

VI. RESULTS

This section discusses the results from the experimental trials. As explained in figure 3, the collected data is processed in the data analysis and processing unit, which is the XCAP-M post-processing software.

The UAV is flown at a height of 60 m in the path shown in the figure 7. This map starts in Cranfield University and flies all the way to Broughton, Milton Keynes. It crosses two cell boundaries during the flight.

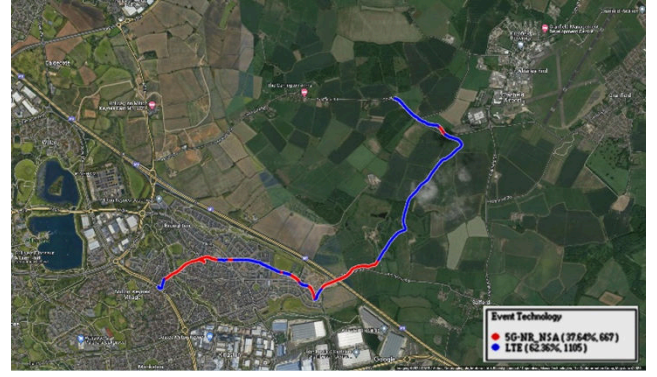


Fig. 7: Flight Path demonstrating connectivity of UAV to heterogeneous networks

The blue highlighted parts show the areas where the UAV is connected to the LTE network, which is most dominant in the initial phases, as 5G has not been deployed in the vicinity of Cranfield University yet. The red parts show the 5G connectivity areas, these are areas where 5G operates as NSA technology.

A. Outcomes of Performance Metrics

RSRP: Firstly, the RSRP is plotted against time. Figure 8 shows this plot, the X-axis shows the time, which have been converted time stamps from the experimental trials, while the Y-axis shows the RSRP values.

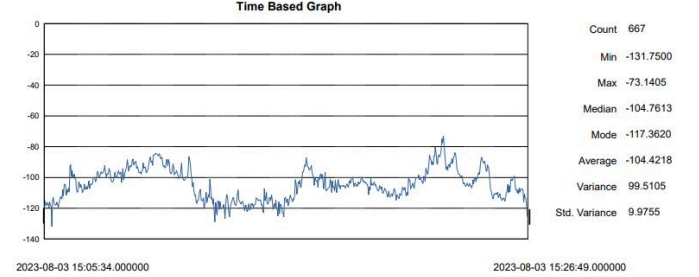


Fig. 8: RSRP vs Time

RSRP sees variations in the form of peaks and troughs, which is indicative of handover being performed. The RSRP sees an average value of -104.42 dBm with maximum and minimum values of -73.14 dBm and -131.75 dBm.

To better understand the performance of the link, the following plots shown in figure 9 10 is used.

It is observed that in figure 9, the RSRP values are completely dropped off for a brief period before starting to measure again. This can be explained by the fact that, the UAV was connected to only the LTE network during this brief period of time. However, as evidenced by figure 10, it always remains connected to LTE. This is due to the NSA 5G feature, it means that at a given point where the UAV is connected to 5G, it will always have the option of switching back seamlessly to LTE should the parameters of

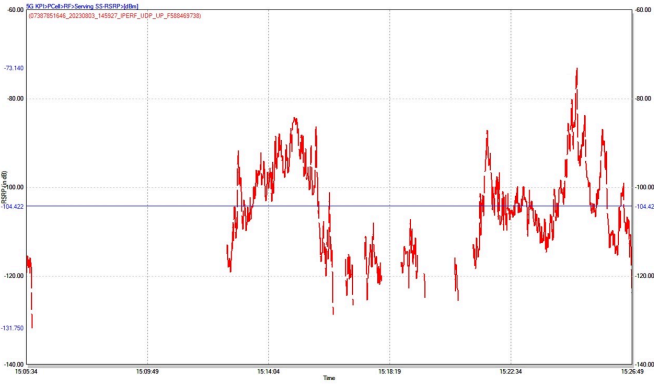


Fig. 9: 5G RSRP

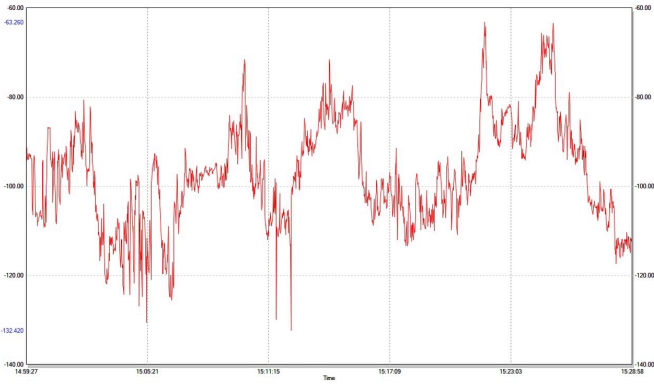


Fig. 10: LTE RSRP

5G deteriorate.

From a handover perspective, the RSRP distribution graph and statistics provide critical insights into the signal strength variations experienced during the handover process. The majority of RSRP values fall within the -110 to -100 dBm range, representing 47.83% of the measurements, indicating frequent instances of weak signal strength. This weak signal

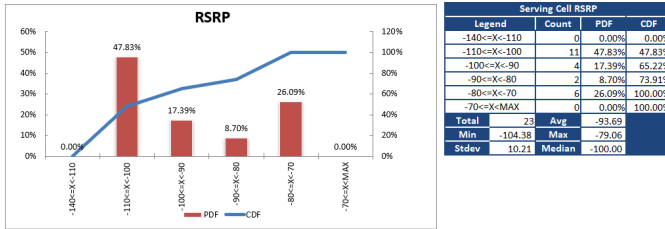


Fig. 11: Probability Density (PDF) and Cumulative Distribution Function (CDF) for RSRP

strength suggests that the UAV often transitions through areas with poor coverage, necessitating handovers to maintain connectivity. However, 26.09% of the measurements show stronger signals in the -80 to -70 dBm range, indicating that the UAV occasionally encounters areas with better

coverage. The cumulative distribution function (CDF) shows that 73.91% of the measurements have RSRP values below -80 dBm, underscoring the challenge of maintaining strong signal strength throughout the UAV's path. The standard deviation of 10.21 dBm suggests moderate variability in the signal strength, reflecting the dynamic nature of the UAV's movement through different network cells. Overall, these observations highlight the variability in signal strength during handovers, affecting the UAV's network performance and stability.

SINR: Similar to RSRP we also plot SINR and throughput for studying the handover. As shown in figure 12 and figure 14. It is seen that, a maximum SINR value of 32.23 dB and an average of 12.33 dB. Similarly, it is seen that, throughput shows maximum and minimum values of 2.42 Mbps and 0.30 Mbps respectively.

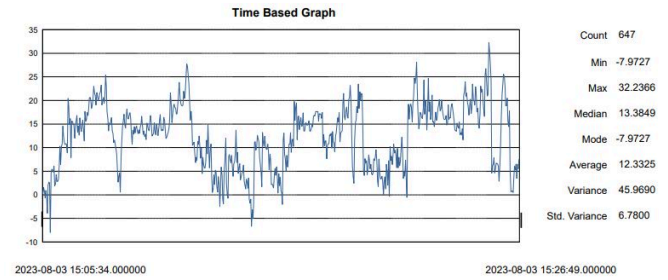


Fig. 12: SINR vs time

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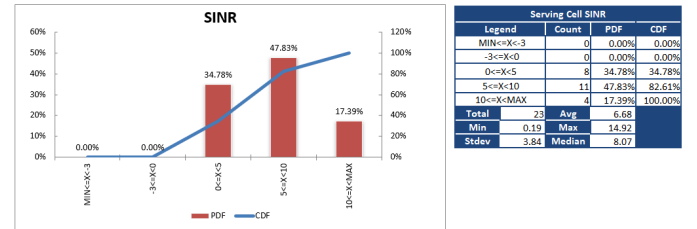


Fig. 13: Probability Density (PDF) and Cumulative Distribution Function (CDF) for RSRP

Figure 14 represents network throughput measured over time. Over approximately 21 minutes, 669 throughput measurements were recorded, reflecting the UAV's transition between different network cells. The throughput varied significantly, from 0.0000 to 2.4214, with an average of 0.3085. The variance and standard deviation were 0.1150 and 0.3391, respectively, highlighting the high variability in network performance as the UAV moved between coverage areas. These fluctuations underscore the impact of handover events on network stability and throughput.

Handover Count: Table III shows the overall, 5G to 5G and LTE to 5G handover summaries. It shows the total HO attempts, the successful HOs and failed HOs. 16 HOs, are attempted by the UAV while, handing over from 5G base

TABLE III: Overall 5G-NR Handover Summary

Statistics	Value	
No. of Ho Attempt	40	
No. of HO Success	40	
No. of HO Failure	0	
Avg. HO Duation (ms)	15	
	Success (%)	Failure (%)
Overall Results	100%	0%
5G NR to NR Handover Summary		
Statistics	Value	
No. of HO attempt	16	
No. of HO Success	16	
No. of HO Failure	0	
Avg. HO duration (ms)	18	
	Success(%)	Failure (%)
Overall Results	100%	0%
LTE to NR Handover Summary		
Statistics	Value	
No. of HO attempt	24	
No. of HO Success	24	
No. of HO failure	0	
Avg. HO duration (ms)	13 ms	
	Success (%)	Failure (%)
Overall Results	100%	0%

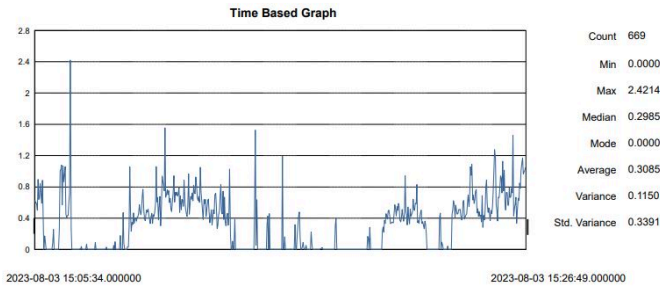


Fig. 14: Throughput vs time

station to another 5G base station and as seen all of them are successful. Meanwhile, between LTE and 5G 24 HO attempts are made all of which are successful. Overall 40 HO attempts are made over a time period of 15 ms.

Figure 15 shows the technology to which the UAV is connected to at each time instance. The transitions show the handover as the UAV moves along its path. As expected the UAV switches from LTE to 5G and then back, based on which one is better. This plot primarily focuses on only two major kinds of technology. However, in reality LTE has sub technologies based on the carrier aggregations (CAs). A detailed plot, outlining the percentage of technologies that the UAV is connected to is shown in figure 16

Figure 16, shows that the UAV stays connected to 5G network 37.64% of times, while LTE presents a 61.68 % connectivity rate. It is also observed that different kinds of LTE CAs show connected status: 0.45% for LTE 2CA and 0.23% LTE 3CA.

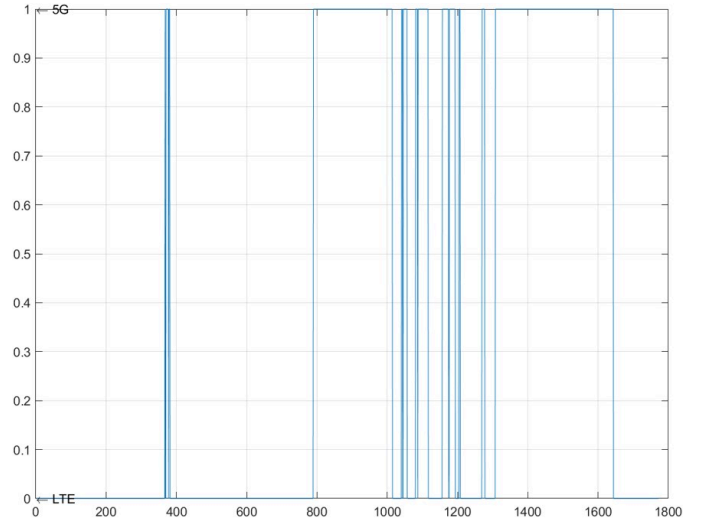


Fig. 15: Network Status

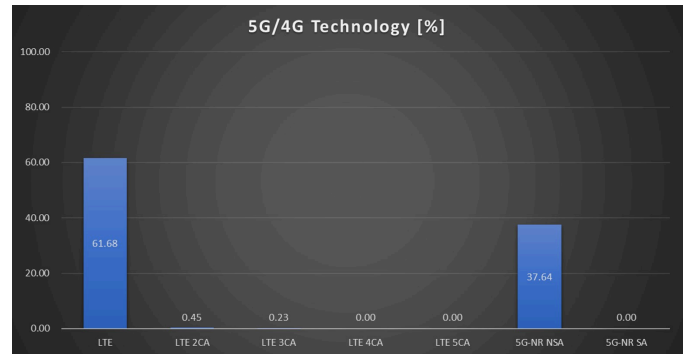


Fig. 16: Network Status in Percentage

VII. CONCLUSION

This study provides a comprehensive evaluation of the impact of UAV handovers in next-generation heterogeneous networks by examining key QoS metrics. Utilizing a DJI F450 UAV equipped with an XCAL tool, the experimental trials traced specific flight path and gathered essential performance data. The findings offer significant insights that are instrumental for the optimization of UAV-centric next-generation networks. The experiments revealed that UAVs can maintain robust connectivity across various network technologies, with successful handovers between two different kinds of networks, evidenced by a 100% success rate for all handover attempts. The analysis of RSRP and SINR values highlighted the impact of handover in signal strength. Future research should focus on refining handover algorithms to enhance signal stability and minimize latency. Additionally, expanding the scope to include different UAV models and flight environments will provide a broader understanding of the operational challenges and potential solutions. The integration of AI-driven handover decision algorithms will further elevate the performance of UAV-based communications across heterogeneous surfaces. Thus, this work not only underscores the feasibility of effective UAV handovers in heterogeneous network environments but also sets the stage for future innovations that will drive the evolution of next-generation UAV communication systems.

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Warrier, Anirudh; Al-Rubaye, Saba; Tsourdos, Antonios

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