Network Performance and Technological Feasibility of Unmanned Aerial Vehicles for Network Extension

Hashsim Alawadi
Department of Computer Science
Computer Science and Mathematics
University of Kufa .Najaf, Iraq
hashima.alawady@student.uokufa.edu.iq
Orcid.org/0009-0009-1577-1426

Salah Albermany
Department of Computer Science
Computer Science and Mathematics
University of Kufa .Najaf, Iraq
salah.albermany@uokufa.edu.iq

DOI: http://dx.doi.org/10.31642/JoKMC/2018/110114

Received Oct. 15, 2023. Accepted for publication Jan. 21, 2024

Abstract*— The operational range of conventional and license-free radio-controlled drones is limited due to line-of-sight restrictions (LoS). There exists a definitive method for operating a drone. Consequently, in order to fly the drone beyond the visual line of sight (BVLoS), it is necessary to replace the drone's original wireless communications equipment with a device that requires a licence and is connected to a cellular network. Long-Term Evolution (LTE), a terrestrial communication technique, enables a drone to establish a real-time connection with a ground station. This connection serves the goals of command and control (C&C) as well as payload delivery. Nevertheless, it is important to note that the electromagnetic environment undergoes changes as altitude increases, which can potentially complicate the process of interfacing with drones over terrestrial cellular networks. The objective of this article is to develop a prototype control system for low-altitude microdrones using LTE technology. Additionally, it seeks to assess the feasibility and effectiveness of cellular connectivity for drones operating at various altitudes. This evaluation will be conducted by examining factors like as latency, handover, and signal strength. At a certain altitude, the received signal experiences a decrease in power level by 20 dBm and a degradation in signal quality by 10 dB. The data throughput of the downlink had a fall of 70%, while the latency exhibited an increase of 94 ms. Despite meeting the basic criteria for drone cellular connection, the existing LTE network necessitates enhancements in order to expand aerial coverage, mitigate interference, and minimise network latency.*

Keywords— UAV, Drones, Energy Conservation, wireless, cellular, 4G, LTE

1. INTRODUCTION

Unmanned aerial vehicles (UAVs), generally known as UAVs, have a wide range of applications, including but not limited to inspection, surveillance, imaging, package delivery, medical, industrial, and agricultural usage [1,2]. In order to securely operate drones, it is imperative to have robust and reliable wireless connectivity for both command and control (CC) as well as payload communications [3]. The utilisation of drones and similar technologies has the potential to significantly enhance the safety of intrinsically hazardous occupations. According to recent research conducted by scholars [4, 5], it has been determined that the cellular network plays a pivotal role in facilitating the development of advanced drone applications. Cellular networks provide wide-area access with high data rates, low latency, and reliable connectivity for both terrestrial and drone user equipment (UE) [5] [6]. The utilisation of low-cost single-board computers offers several benefits, such as decreased energy consumption and compatibility with a diverse array of peripheral devices, including communication chips and antennae. Consequently, the system design encompasses network nodes that provide communication between these devices and end users or other entities within the corporate network. In the realm of consumer electronics connectivity, the Long-Term Evolution (LTE) cellular standard emerges as the predominant choice. As per the specifications outlined in IEEE 802.11, both infrastructure and ad hoc modes of operation are considered to be feasible options. Every approach possesses a distinct array of advantages and disadvantages that are contingent upon the particularities of the given application. The IEEE 802.11a/b/g/n/ac standards, along with all preceding iterations of the 802.11 protocol. To ensure compatibility with a wide range of wireless devices, it is recommended to enable support for both 802.11b/g/n and 802.11a/b/g/n/ac standards inside the Industrial, Scientific, and Medical (ISM) wireless bands. This can be achieved by enabling transmission at both the 2.4 GHz frequency range, which supports 802.11b/g/n, and the 5 GHz frequency range, which supports 802.11a/b/g/n/ac. The intelligent wireless communication system, also known as Software-Defined Radio (SDR), is constructed based on the principles of software-defined radio (CR) [7]. Instead of relying on hardware components, the cognitive radio's channel-switching capabilities are implemented through software, enabling the adjustment of the software-defined radio's broadcast frequency. In order to enhance the performance of channel-switching, cognitive radio (CR) actively monitors the status of the local radio spectrum [8]. The advancement of Internet of Things (IoT) applications utilising 5G technology is significantly dependent on Cognitive Radio (CR) as a crucial technical facilitator [9]. However, cognitive radio (CR) possesses advantageous characteristics that make it suitable for broader implementation of unmanned aerial vehicles (UAVs). These include decreased energy consumption and latency, efficient utilisation of spectrum resources based on specific application needs, and improved security due to CR's resistance to certain conventional attacks.

2. LITERATURE REVIEW

The initial stage in the development of an unmanned aerial vehicle (UAV) utilising cognitive radio (CR) technology involves the selection of a suitable software-defined radio (SDR)-UAV combination. There is a notable focus on software-defined radio (SDR) tools and programmes in the context of studying and investigating wireless networks from an aerial perspective [10]. Regarding miniature unmanned aerial vehicles (UAVs), they offer power measurements, establish standards for software-defined radio (SDR) technology, and provide components for SDR hardware. In addition, the company provides services such as SDR software calibration, SDR software benchmarking, and adherence to SDR software source code standards. The authors arrive at the conclusion and subsequently provide the recommendation that Recent studies have also focused on the use of CR aircraft. Conducted a study on the utilisation of Continuous Improvement (CR) methodologies within the context of the aviation sector [11]. Although the survey lacks comprehensiveness, the data presented regarding the utilisation of CR and UAS in research holds significant relevance for the broader application of unmanned aerial vehicles (UAVs). However, the researchers reached the conclusion that further investigation into the integration of cognitive radio (CR) with unmanned aerial vehicles (UAVs) was necessary [12]. The participants engaged in a comprehensive examination and analysis of various difficulties, challenges, and potential avenues for study within the field. Different iterations of unmanned aerial vehicles (UAVs) have been employed to establish the foundation for aerial networks in diverse regions, and research in this domain is progressing significantly [13, 14]. Frequencies within the ISM, IEEE-S, and IEEE-L bands are frequently employed by aerial robots. Saleem et al. provide supporting data by citing the expansion of wireless devices operating within these frequency ranges. One potential solution to address the scalability challenge is the integration of cognitive radio technologies and unmanned aerial vehicle (UAV) communications [15]. According to the authors, cognitive radio presents novel challenges in the upper tiers of communication infrastructure. This article examines the functioning of routing in Wireless Sensor Networks (WSNs). Just like in the case of UAV networks, this particular situation poses routing difficulties due to the high mobility of UAVs and the utilisation of insufficient planar graph models and techniques for 3D in most existing ad hoc routing algorithms [16]. However, as indicated by the authors, it is uncertain whether this adjustment alone would suffice to enhance their performance, despite the apparent advantages of their planning technique in this particular scenario. Research has also been conducted on Unmanned Aerial Vehicle (UAV) networks that exhibit resilience towards delays. A self-governing aerial Long-Term Evolution (LTE) node was created with the purpose of transporting data in a suboptimal network setting [17]. This is accomplished by the utilisation of a routing methodology that relies on the delay of epidemic spread. The field of flight planning constitutes a distinct area of study within academia [18, 19]. The authors propose the utilisation of wireless communication services as a means to establish interconnectivity among unmanned aerial vehicles (UAVs). Based on the compelling findings, the researchers devised a planning system for unmanned aerial vehicles (UAVs) that restricts their flight operations within a specified coverage radius, thereby circumventing areas with no signal reception [19].

3. METHODOLOGY

Intel Galileo Gen 1 is primarily beneficial for academic studies. The Linux operating system, specifically the Linux Quark 3.19.8 Yocto-standard version, was operational on a chipset that was compatible with its requirements. The Linux image was produced by utilising BSP 1.2, the Intel IoT Development Kit (iot-devkit), and a significantly customised Linux Kernel 3.19.8. These components were employed to construct a platform that encompasses the essential connectivity choices [20]. In order to supply power to the Galileo board, an additional battery with a capacity of 10400 mAh was connected. The battery has the capacity to sustain Galileo for a maximum of 15 hours, contingent upon the specific mode of operation and the level of traffic. Additional details regarding the process of ageing can be found in the findings section. The Intel Dual Band Wireless-AC 7260 LTE card was linked to the PCI Express slot of the Galileo motherboard. The Ethernet card exhibits compatibility with a diverse array of LTE protocols, encompassing IEEE 802.11a/b/g/n/ac, thereby enabling data transfer rates of up to 867 Mbps. The wireless gadget has the capability to serve as an intermediary connecting two distinct networks [21]. Furthermore, we implemented a set of external antennas, characterised by a 5 dBi omnidirectional gain and a wide coverage area. The combined weight of the motherboard, batteries, and antennas is around 340 grammes [22]. The term "grammes" refers to a unit of measurement commonly used in the metric system The remaining actions are delineated comprehensively, divided into three distinct components. Based on preliminary theoretical investigation [23], we have successfully demonstrated the coverage range of an Unmanned Aerial Vehicle (UAV) including an Intel Galileo board, which functions as a Long-Term Evolution (LTE) node. The Free Space (or Friis) and Wireless World Initiative New Radio (WINNER) D1 models consider the outdoor environment as a viable medium for the propagation of radio waves, owing to their ability to traverse through empty space. The models were utilised to make predictions regarding the maximum radio coverage for uplink and downlink in various implementations of the LTE standard [24].

A. *Unmanned Aerial Vehicles (UAVs)*

Unmanned Aerial Vehicles (UAVs) are commonly referred to by several terms, such as drones and unmanned aerial systems (UAS). However, it is commonly observed that in the majority of instances, the two phrases refer to the identical concept [25]. The term "unmanned aerial vehicle (UAV)" refers to a computer-equipped aircraft, as stated within the context of this article. Unmanned Aerial Vehicles (UAVs) possess the capability to be either remotely controlled or operate autonomously, hence enhancing their versatility in performing a diverse array of jobs. The individuals Numerous commercial and scientific applications, including as traffic monitoring, communication relays, crisis management, and data and image gathering, are presently undergoing development [26]. Table 1 [27] provides an overview of the various classifications of unmanned aerial vehicles (UAVs) based on their dimensions, flight altitude, and endurance. Figures 1 and 2 provide visual evidence indicating that the F450 quadcopter possesses dimensions that classify it as a comparatively little unmanned aerial vehicle (UAV).

Table 1 presents the categorization of unmanned aircraft, often known as UAVs, based on the research conducted in reference [27].

UAV	Weight (kg)	Altitude (km)	Endurance (h)
Micro	0.1	0.25	1
Mini	<30	0.15–0.3	<2
Short range	200	3	2–4
Medium range	150–500	3–5	30–70
Long range	-	5	6–13
Endurance	500–1500	5–8	12–24
Medium altitude,	1000–1500	5–8	24–48
long endurance High altitude long endurance	2500–12,500	15–50	24–48

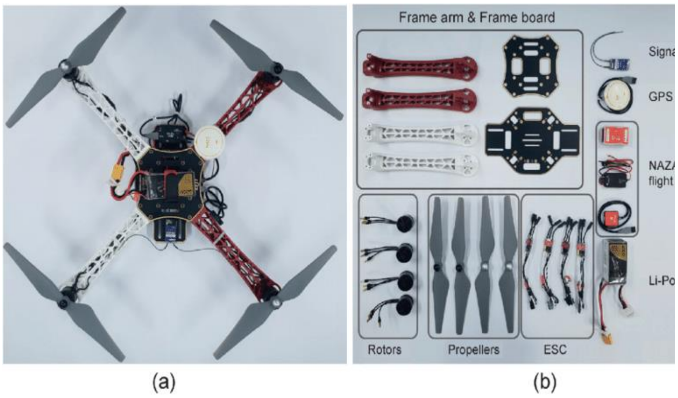


Figure 1. F450 quadcopter a- assembly and b- its components, UAV weighing around 2.25 kg and capable of a flight time up to 20 min.

Figure 2. The developed drone prototype with an LTE-based control system.

This study primarily centres on the communication aspects of unmanned aerial vehicles (UAVs), with particular emphasis on the challenges provided by their small-scale dimensions, including limited battery capacity, compact physical structure, and weight restrictions. The battery constitutes a significant proportion of the overall weight of the miniature drones. For example, an F450 quadcopter powered by a 2200 mAh battery is employed. Moreover, it is noteworthy that batteries constitute about 30 percent of the total weight of the aircraft. However, it is important to highlight that the aircraft's flight duration is limited to approximately 20 minutes when relying solely on a single charge.

B. *Energy conservation*

Is a crucial aspect of sustainable development and environmental preservation. It involves the efficient use and management of energy resources to minimise waste and reduce negative impacts on the environment.

Unmanned aerial vehicles (UAVs) exhibit a diverse range of forms and dimensions, with each configuration strategically designed to enhance performance in specific missions. To develop accurate and practical energy consumption models, it is important to possess a comprehensive understanding of the variables that impact energy consumption. According to a study conducted by researchers [28], it has been found that the power consumption of drones is higher compared to that of conventional automobiles. The consumption of energy can be influenced by a combination of internal and external factors. The achievement of reduced power consumption resulting from the increased translational lift exerted by the UAV during the transition from hovering to forward flight was facilitated by the deliberate choice to fly against a headwind [29]. The ambient temperature and air density have an impact on both the battery drain and lift capacity of an aircraft. Unmanned aerial vehicles exhibit diminished operational capabilities and an elevated susceptibility to malfunction in sub-freezing temperatures, namely below 32 degrees Fahrenheit. In the context of power requirements for unmanned aerial vehicles, weight and payload emerge as crucial factors [30]. This study investigates the impact of several energy-related factors on the unmanned aerial vehicle (UAV) routing problem. This study examines a scenario example using a single unmanned aerial vehicle (UAV) mission that encompasses many delivery tasks, ultimately leading to the aforementioned conclusion [31]. This investigation aims to examine the potential links between the energy consumption of unmanned aerial vehicles (UAVs) and the diverse elements that influence their energy usage. This necessitates a heightened focus on doing research and assessing the patterns of power consumption exhibited by drones. In the subsequent section, we will conduct a more detailed examination of the four primary aspects, namely drone design, the surrounding environment, drone dynamics, and delivery operations, which exert an influence on the energy requirements of a drone. The user has provided a numerical sequence consisting of the numbers 32 and 33. The utilisation of lithium polymer (LiPo) batteries is prevalent in micro drones, as these batteries possess a limited power capacity. Consequently, it becomes imperative to monitor and assess the specific power requirements of each individual micro drone [34].

An excellent style manual for science writers is [7].

4. THE RESULTS

In this study, we present the outcomes of flight experiments conducted at several altitudes while utilising a commercial Long-Term Evolution (LTE) network. Additionally, we provide a graphical representation illustrating the energy consumption of the drone during the duration of the testing period.

C. Ground-Level Field Evaluation

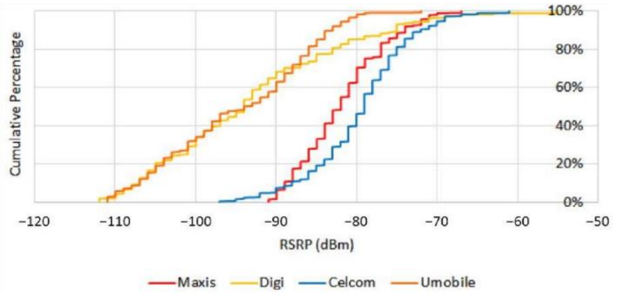
Prior to selecting a reliable supplier for the drone drive test, we conducted a terrestrial drive test to evaluate and compare the Radio Signal Received Power (RSRP) and data rate performance of four potential telecommunications service providers. The measurement of received signal strength (RSRP) holds significant importance in Long-Term Evolution (LTE) networks, and its calculation can be performed using the following methods.

$$RSRP = RSSI - 10\log_{10}(12 \times N)$$

The received signal strength indicator (RSSI) quantifies the magnitude of a signal's power. The bandwidth for RSSI measurement of an E-UTRA carrier is capable of accommodating N resource blocks. The RSSI, derived from measurements obtained within OFDM symbols, encompasses the collective power of intracell power, interference, and noise, hence providing an average representation.

The driving evaluation results are presented in Figure 3 as a cumulative proportion of the proposed retail price. The Received Signal Reference Power (RSRP) of Maxis' network exceeds 75 dBm for 90% of the time and consistently surpasses 90 dBm.

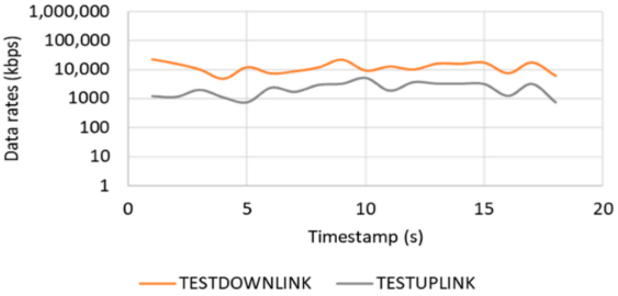
Figure 3. *RSRP* distribution at ground level.



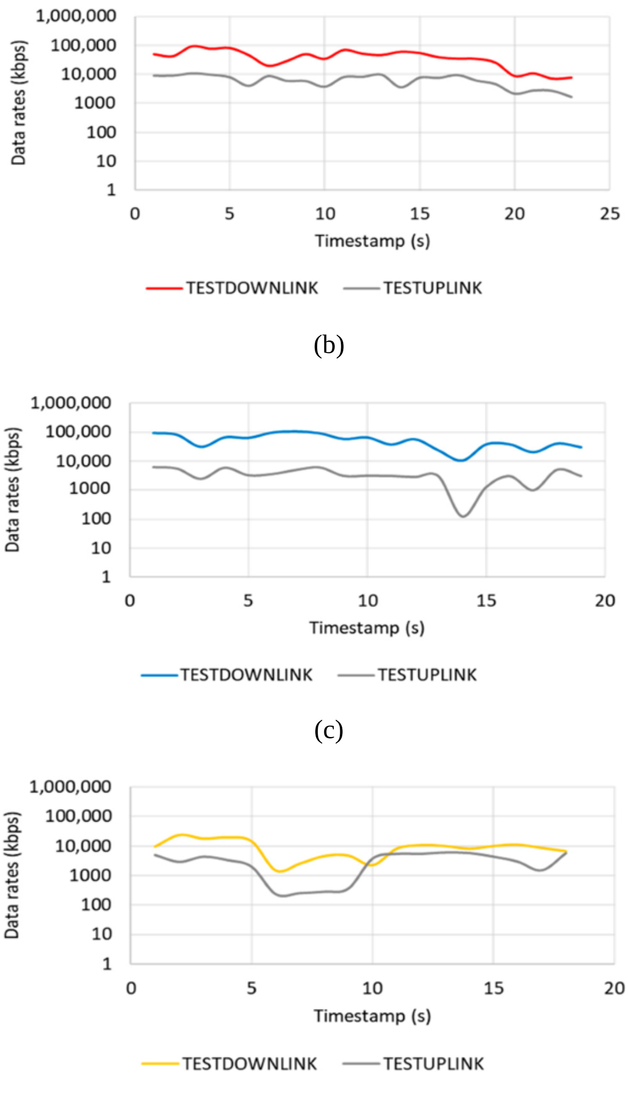
The data transmission rates for four service providers are depicted in Figure 4. According to the data, Maxis offers a downstream speed of 41,331 kbps, which is the fastest among the available options. Additionally, Maxis gives the fastest uplink speed of 6451 kbps. Further study is conducted on the Maxis network using the measured Reference Signal Received Power (RSRP) and uplink throughput.

D. Greater Altitudes Field Test

The cumulative distribution of altitudes is depicted in Figure 5. The initial investment for incorporating additional height is higher. Based on the findings presented in references (1) to (3), the observed behaviour may be mostly attributed to the positive correlation between altitude with the likelihood of line-of-sight (LOS) communications. Consequently, this relationship leads to a decrease in the occurrence of route loss. Moreover, in cases where the altitude of the drone exceeds a certain threshold, the path loss can be likened to the propagation that occurs in unobstructed space. This relationship is demonstrated by Equations (5) and (6). Nevertheless, the received signal reference power (RSRP) experiences a significant decrease as the drone ascends to higher altitudes, specifically at 170 metres. The proportional relationship between the length of the cable and the separation between the drone and the eNodeB results in path loss, as well as a decrease in aerial gain and eNodeB power. By elevating the height of the eNodeB antennas, the likelihood of drones being served by primary lobes is reduced. The use of drones will rely on the lower aerial gain sidelobes of antennas positioned at higher altitudes, as opposed to the primary lobes of eNodeB antennas that provide assistance to user equipment (UEs) at lower altitudes. However, it should be noted that the Received Signal Reference Power (RSRP) values at different altitudes range from 65 to 85 dBm. This indicates that the drone's signal coverage is adequate for the measured dimensions.



(a)



(b)

(c)

(d)

figure 4. Data rates by different mobile network operators: (a) Umobile, (b) Celcom, (c) Maxis, and (d) Digi.

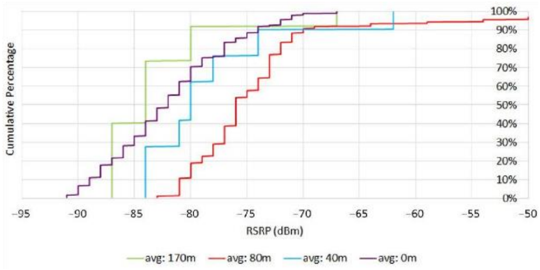
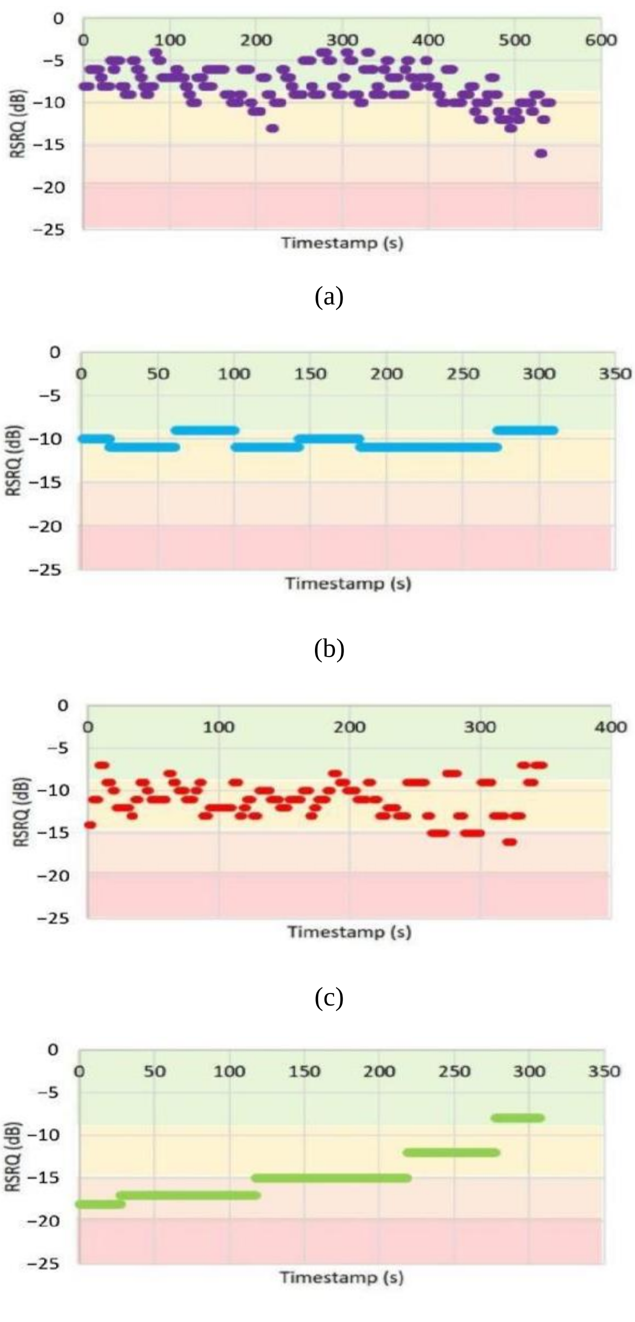


Figure 5. Reference signal received power (*RSRP*) distribution at different altitudes.

An important statistic for gauging the impact of neighbouring eNodeBs on overall network reception quality is the received signal strength ratio (RSRQ). Here's how the RSRQ is follows:

$$RSRQ = \frac{N * RSRB}{RSSI}$$

Figure 6 displays numerous instances of the Radio Signal Received Quality (RSRQ) at various elevations. The results indicate that increasing the height has a significant impact on reducing the Reference Signal Received Quality (RSRQ). The probability of having a clear line-of-sight and the minimum permissible signal strength both increase as the size of the system increases. However, the probability of experiencing interference from neighbouring cells also increases. Airborne user equipments (UEs) has a significantly broader range of detection for neighbouring evolved NodeBs (eNodeBs) in comparison to ground-based UEs. Therefore, an increased amount of interference radiation originating from adjacent cells is received by user equipment (UEs) in the atmosphere.



(a)

(b)

(c)

(d)

Figure 6. Reference signal received quality (*RSRQ*) distribution at (a) 0 m, (b) 40 m, (c) 80 m, (d) 170 m.

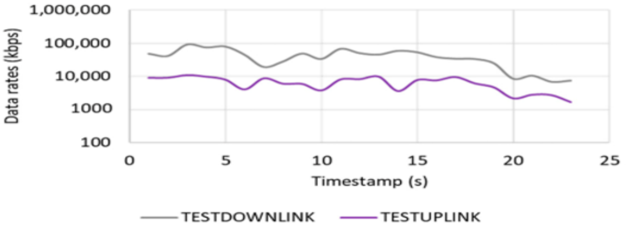
Upon comparing the findings, it becomes evident that the RSRQ level has a significant decline at elevated elevations, specifically at 170m. This phenomena can be attributed to the 'umbrella effect,' wherein eNodeB antennas are oriented in a downward direction to enhance ground coverage. Furthermore, when operating at elevated altitudes, the drone is highly susceptible to potential disruptions caused by the downlink transmissions of adjacent cellular network sidelobes. There is a projected expectation that drones operating at heights above the eNodeB will encounter a notable escalation in interference levels when utilising terrestrial LTE networks.

E. *Comparison of Uplink and Downlink Throughput to 3GPP Specification*

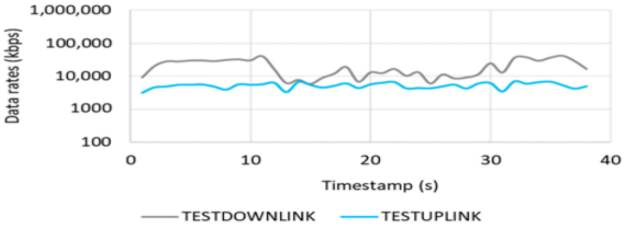
The performance of drones is influenced by the throughput metrics when operating on an LTE cellular network. In order to transmit a real-time video stream to the base station, it is necessary for the drone's uplink throughput to adhere to the specifications outlined in the 3GPP Release-15 [35] documentation. The movie associated with the programme is of considerable size, hence requiring a substantial amount of bandwidth.

The adherence to the 3rd Generation Partnership Project (3GPP) standards pertaining to command and control is of utmost importance in order to guarantee the effective functioning of drone control systems. Successful CC communications necessitate an uplink data bandwidth of 200 kilobits per second, an error rate of less than 0.1% per packet, and a network latency of less than 50 milliseconds. Payload communications of drones often involve the transmission of real-time telemetry data, images, or videos captured by aerial cameras or other remote surveillance devices. The current network infrastructure of the drone enables data speeds of up to 4 Mbps, which are insufficient for the transmission of 1080p video content.

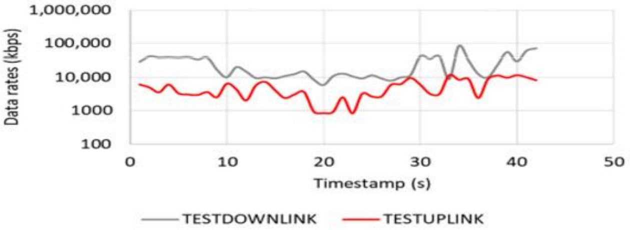
The findings from the field experiments, as depicted in Figure 7 and summarised in Table 2, suggest that the LTE network being examined has the potential to offer satisfactory data rates and acceptable network latency for both command and control (CC) and payload transmission in drone applications. The findings indicate a positive correlation between network depth and latency, implying that applications requiring low latency, such as real-time remote control, would require increased maintenance efforts. Specifically, these applications would necessitate a network latency of less than 20 ms.



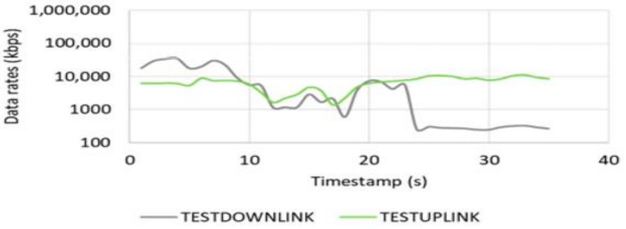
(a)



(b)



(c)



(d)

Figure 7. Data rates at 0m (a), 40m (b), 80m(c), and 170m (d).

Table 2. Average throughput and delay.

Elevation	0 m	40 m	80 m	170 m
Average Uplink Throughput (kbps)	6451	5245	5051	6737
Average Downlink Throughput (kbps)	41,332	20,164	24,699	7893
Average delay (ms)	25.4	24.73	23.44	36.63

F. *Influence of Fly Height on Handoff*

The implementation of the LTE network required the elimination of a crucial technological element in the UMTS Soft/Softer handover architecture. The reason for this phenomenon can be attributed to the system's flat topology, the orthogonality of LTE, and the practise of reusing frequencies across adjacent cells [36]. Consequently, it was postulated that the examination would exclusively encompass challenging handoffs. The signal quality of the user equipment (UE) was monitored during the road test to analyse the handoff process between several eNodeBs along the designated route.

The diagram in Figure 8 illustrates the values of relative signal strength (RSRP) and relative signal strength (RSSRQ) for a terrestrial user equipment's path. Based on the available data, it can be shown that there were three distinct locations where ping-pong handoffs occurred, as indicated by the presence of red circles. When a User Equipment (UE) is relocated to a different cellular base station and subsequently returns to its initial base station, a ping-pong handover (HO) process occurs. The majority of assistance provided by the unmanned entities (UEs) during the driving examination was derived from cells 12 and 11. The Received Signal Reference Power (RSRP) experienced a decrease to 95 dBm, but the Reference Signal Received Quality (RSRQ) exhibited an increase to 14 dB upon transferring the link from cell 12 to cell 11.

Figure 9 illustrates the recorded RSRP and RSRQ measurements obtained by the unmanned aerial vehicle (UAV) user equipment (UE) at an altitude of 40 metres. There were three distinct cellular locations situated along the trajectory that offered assistance to the unmanned aerial vehicle (UAV). These locations were designated as Cell 11, Cell 41, and Cell 42. The RSRP and RSRQ values experienced an increase from 78 dBm to 84 dBm and a decrease from 11 dB to 9 dB between Cell 11 and Cell 41. The handoff from cell 41 to cell 42 exhibited a notable rise in the Reference Signal Received Power (RSRP) from 8m to 84 dBm, accompanied by a slight decline in the Reference Signal Received Quality (RSRQ) from 11 dB to 10 dB.

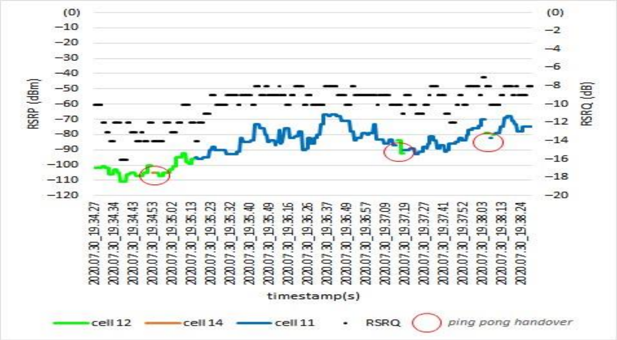


Figure 8. *RSRP* and *RSRQ* level during handover at 0 m (ground level).

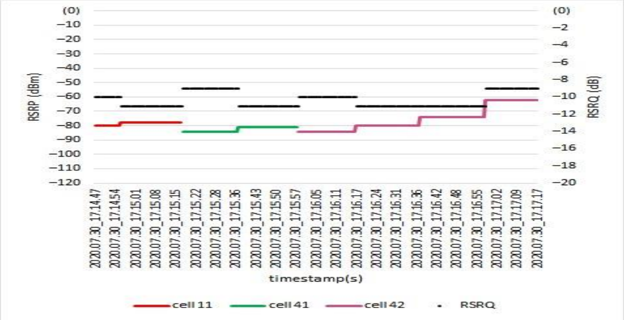


Figure 9. *RSRP* and *RSRQ* level during handover at 40 m.

Figure 10 illustrates the technique of transferring at an elevation of 80 metres. In this particular instance, it was observed that two specific cells, namely cell 1 and cell 11, were tasked with the responsibility of upkeeping the equipment utilised by the drone operator. After being relocated from cell 11 to cell 1, the Received Signal Received Power (RSRP) experienced a decline to 77 dBm, while the Reference Signal Received Quality (RSRQ) decreased to 12 dB.

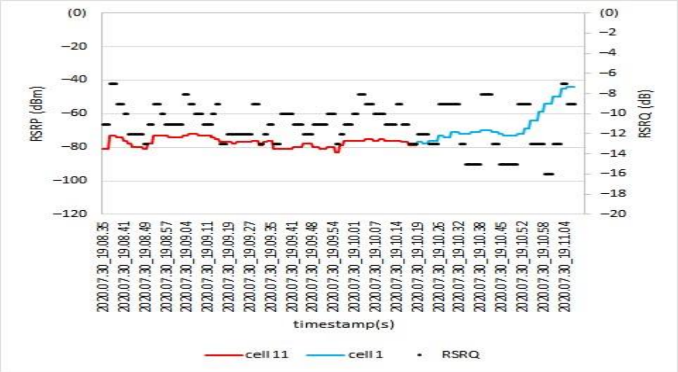


Figure 10. *RSRP* and *RSRQ* level during handover at 80 m.

According to Figure 11, the cells that played a crucial role in supporting the UE during the experiment were Cell 16, Cell 12, and Cell 11. The RSRQ level experienced a decrease from 18 dB to 17 dB following its transition from Cell 16 to Cell 12. To achieve optimal performance, it is necessary to ensure a minimum received signal reference power (RSRP) level of 87 dBm. The Received Signal Reference Power (RSRP) exhibited a decline from 84 dBm to 15 dB, while the Reference Signal Received Quality (RSRQ) experienced a fall from 17 dB to 15 dB during the transition from Cell 12 to Cell 11.

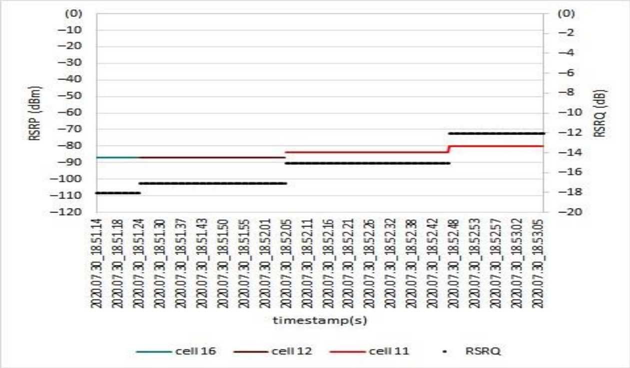


Figure 11. *RSRP* and *RSRQ* level during handover at 170 m.

The degradation of signal quality in drones can be observed by the graphical representations provided in Figures 8-11. The object experienced an increase in elevation as it ascended. However, there was no interruption observed in the handoff process, such as a rapid decrease in signal intensity, over the whole transition period.

G. *Environmental Effects on Transition*

The assessment of the impact of the surrounding environment on handover is necessary in order to conduct a comprehensive investigation of the handover process across different elevations. Next, we examine the impact of the height of the eNodeB tower on the timing of handoffs. Table 3 presents the dimensions of the eNodeB towers currently being considered. As depicted in Figure 12, the dimensions of the drone have an impact on the specific cluster of cells from which it draws electrical power. When the drone decreases its altitude below the eNodeB's level, it is generally capable of receiving signal from the eNodeB. In order to provide the most efficient service to terrestrial User Equipments (UEs), the antennas of the eNodeB are oriented in a downward direction. As a result, the user equipment intended for drones will be transported through the primary lobes of eNodeB antennas. The antennas on the eNodeB towers provide coverage to drones that traverse the towers' altitude through the presence of sidelobes. The delivery of the drone user equipment by Cell 12 is supported by the observation of its route height of 170 m, indicating that it is positioned at a greater distance compared to the other cells within this vicinity. This observation provides evidence that Cell 12 exhibits a higher intensity of sidelobe signals compared to other cells, hence indicating the potential presence of the desired route in its vicinity.

Table 3. Cell ID and its height.

Cell ID	Height (m)
1	105
2	94
11	137
12	198
14	56
16	105
42	105
41	88

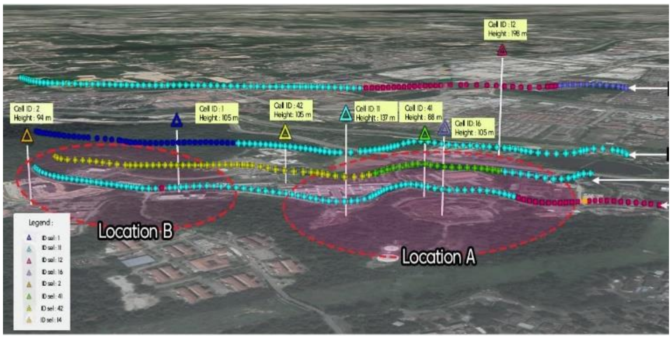
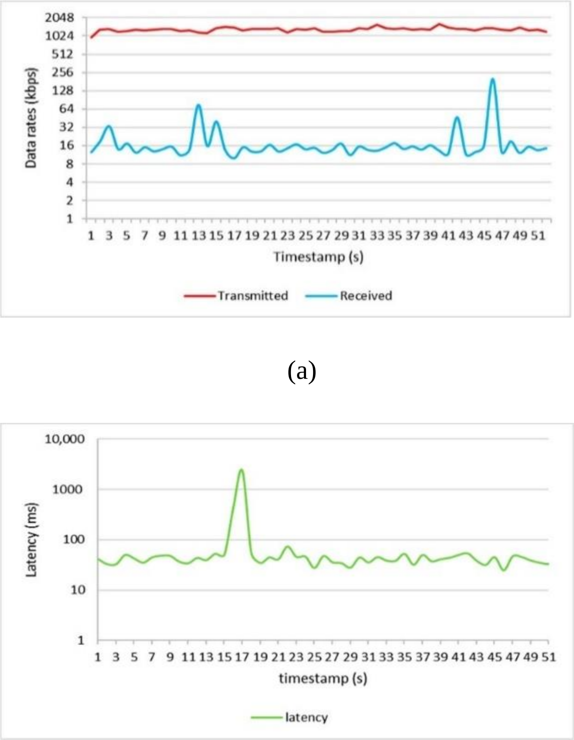


Figure 12. Location of user equipment (UE) and serving cell.

Figure 12 illustrates the division of the research area into two distinct areas, denoted as A and B. This division was implemented to facilitate the separate evaluation of the impacts of physical geography and the surrounding environment. Although the risk of signal loss is more pronounced for drones compared to terrestrial user equipments (UEs), the findings at distances of 0 m and 40 m indicate that drones predominantly depend on neighbouring eNodeBs even when operating at altitudes surpassing the height of structures and vegetation. However, the presence of trees can significantly affect the process of serving cell selection for terrestrial User Equipment (UEs) due to their ability to obstruct signals and create areas of shadowing.

H. *Performance Assessment of Drones*

Figure 13 illustrates the throughput and lag time associated with the transmission of data from the drone to the base station and vice versa. The average delay for uplink and downlink between the drone and ground station was 94 ms, while the average transmission rates for packet data were 1303 kbps and 20 kbps, respectively. Nevertheless, according to the 3rd Generation Partnership Project (3GPP) release-15 standard [37], the maximum data speeds for control channel (CC) communications are specified as 100 kbps, while for payload communications on the uplink, the maximum data speeds are set at 4 Mbps. Additionally, the standard mandates that the latency should be kept below 50 ms. In the context of Beyond Visual Line of Sight (BVLoS) drone applications, the imperative for real-time control and high-fidelity picture or video transmission requires enhanced connectivity, which can be achieved through the optimisation of the existing Long-Term Evolution (LTE) network's performance.



(a)

(b)

Figure 13. Packets data transmitted and received by the drone (a) and its delays (b).

5. REFLECTION: PRACTICAL CHALLENGES AND SOLUTIONS

The primary emphasis of the existing LTE network mostly is in delivering ground-level coverage. The preflight planning process should incorporate the utilisation of a remotely operated unmanned aerial vehicle, commonly known as a drone. Additionally, it is advisable to conduct a preliminary assessment to ascertain the availability of Long-Term Evolution (LTE) network coverage within the designated geographical region. The utilisation of the side lobe of the drone aerial for control purposes is now under deliberation. Throughout the length of the experiment, the drone, assuming the role of a parachute, remained within the service area of the eNodeB. The altitude of drone flights was restricted. Through this research, our aim is to provide a comprehensive analysis of the limitations inherent in the existing LTE design. Additionally, we seek to motivate LTE tower makers to enhance the efficiency and effectiveness of control systems reliant on LTE technology. This paper posits, nevertheless, that Long-Term Evolution (LTE) could potentially have utility in the context of unmanned aerial vehicles (UAVs).

6. CONCLUSION

The objective of this study is to investigate the capabilities and constraints of commercial LTE networks in providing cellular connectivity for beyond visual line of sight (BVLoS) drone operations. The present assumption posits the existence of a prototype drone that has been outfitted with LTE connectivity. Drones have the potential to optimise the operational efficiency of the existing Long-Term Evolution (LTE) network through the transmission of data packets. Specifically, the drone may achieve a data transfer rate of 1303 kilobits per second (kbps) from the drone to the ground station, while in the reverse direction, a rate of 20 kbps can be attained. Furthermore, the round-trip delay for data transmission in both directions is measured at 94 milliseconds. Communication can be characterised by a bidirectional flow, encompassing both upward and downward channels. In light of the aforementioned evidence and analysis, it can be inferred that the conclusions drawn from However, the current 4G network lacks the necessary capabilities to adequately handle the low latency and extensive uplink data capacity needed for sophisticated drone applications. Comprehensive pilot field measurements were conducted in order to have a deeper understanding of the strengths and weaknesses of the existing cellular network. While the current 4G network is capable of facilitating command and control as well as payload communications for beyond visual line of sight (BVLoS) drone applications, further enhancements are imperative to establish a dependable and secure communications link for more advanced drone use cases. This is particularly crucial in relation to minimising overall network latency. Furthermore, it is important to consider the data upload rate.

REFERENCES

[1] Zeng, Y.; Guvenc, I.; Zhang, R.; Geraci, G.; Matolak, D.W. *UAV Communications for 5G and Beyond*; Wiley Online Library: New York, NY, USA, 2020.

[2] Wang, X.; Kealy, A.; Li, W.; Jelfs, B.; Gilliam, C.; May, S.L.; Moran, B. Toward Autonomous UAV Localization via Aerial Image Registration. *Electronics* 2021, *10*, 435. [CrossRef]

[3] Gupta, L.; Jain, R.; Vaszkun, G. Survey of essential issues in UAV communication networks. *Ieee Commun. Surv. Tutor.* 2015, *18*, 1123–1152. [CrossRef]

[4] Zeng, Y.; Zhang, R.; Lim, T.J. Wireless communications with uncrewed aerial vehicles: Opportunities and challenges. *IEEE Commun. Mag.* 2016, *54*, 36–42. [CrossRef]

[5] Mousavi, H.; Amiri, I.S.; Mostafavi, M.A.; Choon, C.Y. LTE physical layer: Performance analysis and evaluation. *Appl. Comput. Inform.* 2019, *15*, 34–44. [CrossRef]

[6] Zeng, Y.; Lyu, J.; Zhang, R. Cellular-connected UAV: Potential, challenges, and promising technologies. *IEEE Wirel. Commun.* 2018, *26*, 120–127. [CrossRef]

[7] Mitola, J. Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio, Doctor of Technology. Ph.D. Dissertation, Royal Institute of Technology, Stockholm, Sweden, 2000; pp. 271–350.

[8] Reyes, H.; Gellerman, N.; Kaabouch, N. A Cognitive Radio System for Improving the Reliability and Security of UAS/UAV Networks. In Proceedings of the 2015 IEEE Aerospace Conference, Big Sky, MT, USA, 7–14 March 2015; pp. 1–9. [CrossRef]

[9] Akpakwu, G.A.; Silva, B.J.; Hancke, G.P.; Abu-Mahfouz, A.M. A Survey on 5G Networks for the Internet of Things: Communication Technologies and Challenges. *IEEE Access* 2018, *6*, 3619–3647. [CrossRef]

[10] Saleem, Y.; Rehmani, M.H.; Zeadally, S. Integration of Cognitive Radio Technology with uncrewed aerial vehicles: Issues, opportunities, and future research challenges. *J. Netw. Comput. Appl.* 2015, *50*, 15–31. [CrossRef]

[11] Powell, K.; Abdalla, A.S.; Brennan, D.; Marojevic, V.; Barts, R.M.; Panicker, A.; Ozdemir, O.; Guvenc, I. Software Radios for Unmanned Aerial Systems. In *Proceedings of the OpenWireless'20, 1st International Workshop on Open Software Defined Wireless Networks*; Association for Computing Machinery: New York, NY, USA, 2020; pp. 14–20. [CrossRef]

[12] Jacob, P.; Sirigina, R.P.; Madhukumar, A.S.; Prasad, V.A. Cognitive Radio for Aeronautical Communications: A Survey. *IEEE Access* 2016, *4*, 3417–3443. [CrossRef]

[13] "Ley 18/2014, de 15 de octubre, de aprobación de medidas urgentes para el crecimiento, la competitividad y la eficiencia," *Spanish Off. Bull.*, vol. 2014, no. 252, pp. 83921–84082, 2014.

[14] L. Song and T. Huang, "A summary of key technologies of ad hoc networks with UAV node," in *International Conference on Intelligent Computing and Integrated Systems*, 2010, pp. 944–949.

[15] L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in UAV communication networks," *IEEE Commun. Surv. Tutorials*, vol. 18, no. 2, pp. 1123-1152, 2016.

[16] Y. Saleem *et al.*, "Integration of Cognitive Radio Technology with unmanned aerial vehicles: issues, opportunities, and future research challenges," *J. Netw. Comput. Appl.*, vol. 50, pp. 15–31, 2015.

[17] J.D.M.M. Biomo, *et al.*, "Routing in Unmanned Aerial Ad Hoc Networks: A Recovery Strategy for Greedy Geographic Forwarding Failure," *Proc. IEEE WCNC Mob. Wirel. Networks*, pp. 2236–2241, 2014.

[18] N. Uchida *et al.*, "Proposal of Seeking Wireless Station by Flight Drones base don Delay Tolerant Networks," *Proc. 9th Int. Conference Broadband Wirel. Comput. Commun. Appl.*, pp. 401–405, 2014.

[19] M. Bekhti *et al.*, "Path Planning of Unmanned Aerial Vehicles with Terrestrial Wireless Network Planning," *Proc. Wirel. Days*, pp. 1–6, 2016.

[20] Intel, "BSP." [Online]. Available: https://downloadcenter.intel.com/download/23197/Intel Quark-BSP. [Accessed: 06-Jul-2016].

[21] H. T. Friis, "A note on a simple transmission formula," in *IRE'46*, 1946, vol. 34 (5), pp. 254–256.

[22] Winner and I. S. Technologies, "IST-4-027756 WINNER II. D1.1.2 V1.2. WINNER II Channel Models," 2008.

[23] A. Neumann *et al.*, "Better Approach To Mobile Ad-hoc Networking (B.A.T.M.A.N.)," *IETF Draft*, 2008.

[24] R. Sanchez-Iborra *et al.*, "Performance evaluation of BATMAN routing protocol for VoIP services: a QoE perspective," *IEEE Trans. Wirel. Commun.*, vol. 13, no. 9, pp. 4947 – 4958, 2014.

[25] Valavanis, K.P.; Vachtsevanos, G.J. (Eds.) *Handbook of Unmanned Aerial Vehicles*; Springer: Dordrecht, The Netherlands, 2015; p. 3022. [CrossRef]

[26] Saleem, Y.; Rehmani, M.H.; Zeadally, S. Integration of Cognitive Radio Technology with uncrewed aerial vehicles: Issues, opportunities, and future research challenges. *J. Netw. Comput. Appl.* 2015, *50*, 15–31. [CrossRef]

[27] Bento, M.D.F. (Ed.) *Uncrewed Aerial Vehicles: An Overview*; Inside GNSS: Hoboken, NJ, USA, 2008; pp. 54–61.

[28] Cheng, C., Adulyasak, Y. & Rousseau, L.-M. (2020), 'Drone routing with energy function: Formulation and exact algorithm,' *Transportation Research Part B: Methodological* 139, 364–387.

[29] Tennekes, H. (2009), The Simple Science of Flight, Revised and Expanded Edition: From Insects to Jumbo Jets, MIT press.

[30] Thibbotuwawa, A., Nielsen, P., Zbigniew, B. & Bocewicz, G. (2018*a*), Energy consumption in uncrewed aerial vehicles: A review of energy consumption models and their relation to the UAV routing, *in* 'International Conference on Information Systems Architecture and Technology,' Springer, pp. 173–184.

[31] Thibbotuwawa, A., Nielsen, P., Zbigniew, B. & Bocewicz, G. (2018*b*), Factors affecting energy consumption of uncrewed aerial vehicles: an analysis of how energy consumption changes about UAV routing, *in* 'International Conference on Information Systems Architecture and Technology,' Springer, pp. 228–238.

[32] Demir, E., Bekta¸s, T. & Laporte, G. (2014), 'A review of recent research on green road freight transportation,' *European journal of operational research* 237(3), 775–793.

[33] Zhang, J., Campbell, J. F., Sweeney II, D. C. & Hupman, A. C. (2021), 'Energy consumption models for delivery drones: A comparison and assessment,' *Transportation Research Part D: Transport and Environment* 90, 102668.

[34] Famili, A., Stavrou, A., Wang, H. et al. (2022), 'Optilod: Optimal beacon placement for high-accuracy indoor localization of drones,' *arXiv preprint arXiv:2201.10691*.

[35] Ng, K.J.; Islam, M.T.; Alevy, A.; Mansor, M.F.; Su, C.C. Azimuth Null-Reduced Radiation Pattern, Ultralow Profile, DualWideband and Low Passive Intermodulation Ceiling Mount Antenna for Long Term Evolution Application. *IEEE Access* 2019, *7*, 114761–114777. [CrossRef]

[36] Monem, M.A.; Netmanias. Why No Soft Handover in LTE? 2016. Available online: https://www.netmanias.com/en/post/blog/11023/handover-lte/why-no-soft-handover-in-lte (accessed on 9 March 2021).

[37] Muruganathan, S.D.; Lin, X.; Maattanen, H.-L.; Sedin, J.; Zou, Z.; Hapsari, W.A.; Yasukawa, S. An overview of 3GPP release-15 study on enhanced LTE support for connected drones. *arXiv* 2018, arXiv:1805.00826.