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Channel Modeling for UAV-Enabled Cellular Networks: A Survey

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Abstract: Unmanned Aerial Vehicles (UAVs) have attracted considerable attention in a wide range of applications including military and civilian area, such as surveillance and monitoring, relief operations and package delivery. Furthermore, UAVs are rapidly growing in networking application and are envisioned as a potential component of 5G wireless technology and beyond. An attractive feature of using UAVs for communication networks is that they can be quickly deployed to support communication backhaul infrastructure as flying base station. UAVs can also be deployed as aerial User Equipments (UEs) in coexistence with ground users. Besides the promising opportunities of UAVs deployment as aerial mobile devices, they rise many technical challenges in order to effectively use them for each specific networking application. An optimal deployment of UAV-enabled communication systems requires using an accurate air-to-ground (A2G) channel model whose characteristics significantly differ from classical ground communication channels. The main goal of this paper is to provide a comprehensive survey on A2G channel modeling for cellular networks in order to support UAV-enabled communications. We present an overview of research works dealing with channel modeling through both simulations and field measurements. Based on the finding of the studied works, a characterization of A2G channel parameters with new aspect is depicted. In particular, we focus on Line Of Site (LOS) propagation, path loss model, interference and fading phenomena in A2G link.

Index terms: Unmanned Aerial Vehicles, Long Term Evolution, Channel Modeling, Pathloss, Interference, SINR, Fading

I. INTRODUCTION

UAVs, also known as drones, have a promising potential to reduce risk, cost, and time deployment for many activities, such as buildings inspection, surveillance and monitoring, search and rescue missions, delivery of medical supplies, and several other use cases [1]-[4]. Owing to their autonomy, flexibility and quick deployment, there has been a tremendous increase in research efforts of both academia and industry since several years. Most of UAV-centric research were robotics or military oriented and had focused on issues of navigation, control, and autonomy. However, the communication challenges of UAVs used to be considered as part of the control and autonomy components and only in very recent years that UAVs communication aspects were considered as a main issue [4], [5]. There exist different types of UAVs that enable to meet a variety of application needs. These latter are specifically related to the characteristics of UAVs such as their capabilities and their flying altitudes. Particularly, the work in [5] suggested a classification of UAVs based on their altitudes, into high altitude platforms (HAPs) and low altitude platform (LAPs). HAPs have altitudes above 17km and are typically quasi-stationary, while LAPs, on the other hand, can fly at altitudes of tens of meters up to a few kilometers, can quickly move, and are more flexible [6], [7].

Among aerial devices connectivity solutions, broadband wireless technologies for public safety scenarios include Long Term Evolution (LTE), WiFi, satellite communications, and dedicated public safety systems such as TETRA and APCO25 were considered [8]. It is worth noting that cellular connectivity was considered as a potential candidate for connecting UAVs for several advantages, such as enabling ubiquitous connectivity based on existing network infrastructure and offering a high likelihood of line-of-sight (LOS) propagation conditions.

This has led to several research works on enhanced Long Term Evolution (LTE) network to support the connected UAVs. Due to the nature of propagation environment in regular cellular communications, radio waves are subject to several phenomena (refraction, reflection and absorption) resulting from their interaction with buildings, trees and other scattering obstacles present in the radio path between ground users and base stations, which attenuates the signal. These phenomena had been studied and modeled respecting several practical scenarios for typical cellular communication use cases, in which the main defects result from the Non-LOS (NLOS) propagation. Although UAVs are also subject to these phenomena, channel models proposed for typical cellular network might not be suitable for aerial scenarios since this propagation environment has its own specificities and characteristics. Indeed, by flying above the ground level and having the flexibility to be positioned in the air and avoid obstacle, UAVs experience an increased likelihood of LOS transmission and can observe an unobstructed path with the serving ground communicating party and with many different interfering equipment in the same area (a base station or user equipment). Hence, 3D channel modeling and characterization is being investigated to enable simulation models and better performance assessment for UAVs use case in LTE cellular network.

We here focus on studies carried out for channel modeling and characterization to enable UAVs connectivity underlying LTE networks. In particular, we provide a survey on field measurements and simulations realized to characterize and assess the

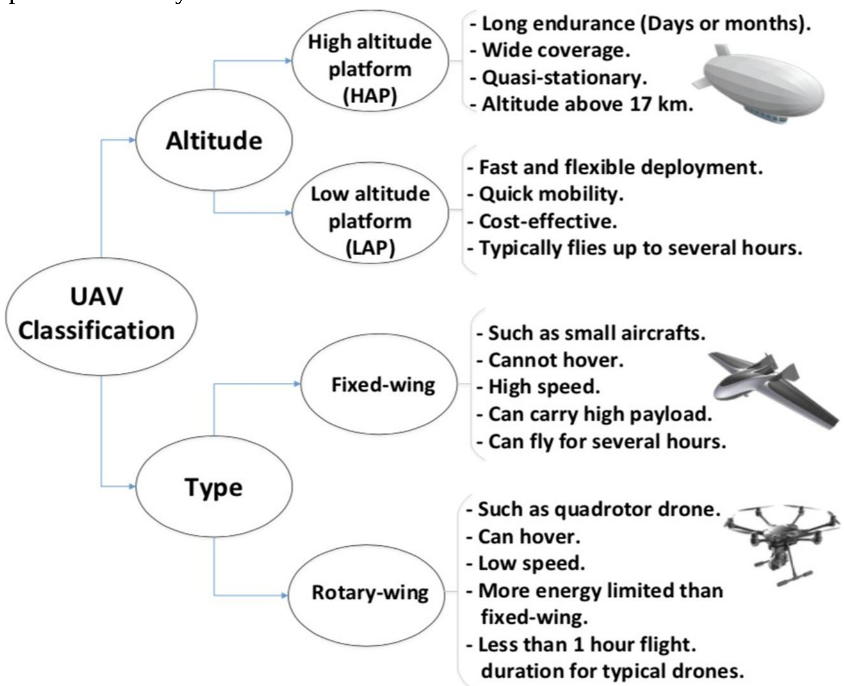

Fig. 1. UAV Classification and characteristics based on the flying altitude (low and high altitude) and the device type (fixed and rotary wings) [5].

Channel parameters in the context of UAV communicating through the cellular LTE network as either a new type of UE, referred to as aerial UE linked to ground BS or flying BS used to mainly enhance coverage. We also present a summary of the findings of these works to synthesize specific aspects of the propagation channels used for UAV over LTE network including those standardized in the 3rd Generation Partnership Project (3GPP) Release 15. These aspects include LOS propagation, pathloss model, interference and signal to noise ratio assessed in a 3D propagation environment.

II. CHANNEL CLASSIFICATION

There have been some efforts to characterize the aerial channel in the literature, which lead to the three main categories: Air to Ground (A2G), Air to Air (A2A), and Ground to Air (G2A) as summarized in [10], [9]. The classification was based on measurements and simulations carried out for different frequencies, altitudes, environments and targeting various applications. Some other studies have focused on measurements and simulations for specific channel model in LTE networks supporting UAV deployed as aerial eNodeB (eNB) and aerial UE [12]-[15].

A. Simulations Scenarios and Field Measurement

The paper in [12] studied pathloss between ground cellular network and low altitude UAV through field measurements conducted in an operating LTE network and performed in a rural environment through measurement. For the experimentation, the authors use a winged UAV with a regular cellular telephone inside its cavity equipped with specific firmware to allow reading and reporting radio measurement for the serving cell and some other neighbor cells every 1s. Measurements include Reference Symbol Received Power (RSRP) and Reference Symbol Received Quality (RSRQ) for a single serving cell configured with 2-degrees electrical downtilt and is located at 22m height above the terrain.

In [13], the authors particularly focused on LTE connectivity for low altitude small UAVs, by first identifying the typical connectivity requirements and characteristics which revealed different propagation conditions for UAVs flying in the sky and mobile users on the ground. Then, simulation results were presented to highlight the feasibility of providing LTE connectivity for small UAVs, followed by a suggestion of several performance enhancing solutions to improve skyward LTE connectivity performance. The main aspects that makes LTE networks challenging for serving UAVs connectivity are the coverage and the interference. Indeed, propagation conditions may be more favorable for UAVs in the sky than for ground users. However, as the number of UAVs increases interference management becomes crucial to avoid performance degradation to ground users. To assess the feasibility of UAVs connectivity underlying LTE network, simulation of rural LTE typical scenario of hexagonal sites grid with 37 sites and 3 cells per site is considered with 10 MHz bandwidth at 700 MHz carrier frequency were carried out in [13]. For aerial channel models, the paper reuses the 3GPP channel models for UAVs at altitudes below BS antenna height and adopt free-space propagation for UAVs at altitudes above BS antenna height. The UE at relatively high altitude (40m and 120m) are served by the sidelobes, with antenna gain less than that of the main lobe that serves the ground UEs, yet the free-space propagations of high altitude UEs can compensate the gain reductions. Furthermore, the results reveal that the free-space propagation also leads to stronger interfering signals from non-serving cells to the UAVs resulting in an SNIR degradation and out of coverage event.

The work in [14] analyzed the use of LTE network to achieve downlink high data volume transfer from UAV UEs and their uplink control through measurements and simulations. The study covers the impact of interference and path loss when transmitting data to and from the UAV UE which is considered as either base stations transmitting in downlink or UEs transmitting in uplink. Furthermore, the impact of deployed aerial UE on the respective downlink and uplink performance of an LTE ground network is analyzed for varying altitude, distance from the base station, or UAV density.

The considered architecture enables UAV UEs and eNodeBs interact with a ground regular LTE network (eNB and UEs). The UE are equipped with omnidirectional antenna to allow them to transmit and receive in any direction without gain or losses, and has a limited transmission power to conserve battery life. Aerial nodes operate similarly to ground with the ability to be placed in a local optimal. When deployed as a UE, a UAV is identical in operation and specifications to a ground UE while it follows the same design rules associated with femtocells if deployed as an UAV-eNB, which is also supposed to have a backhaul connection.

The paper in [11] presents an overview of the 3GGP standard works in supporting the use of UAVs in its 15th release, and focused on connectivity requirements and performance evaluation scenarios, radio channel models and the key identified challenges of using LTE networks to enable UAVs connectivity and suggested potential solutions to address the challenges including interference detection and mitigation techniques, mobility enhancements, and UAV identification. The paper presented the requirements for the two types of data adopted for UAV use cases, which are command and control data and application data. These requirements include latency, UL/DL data rates as well as command and control reliability.

To assess the performance of the UAVs in LTE network, three scenarios are considered to simulate urban-macro, urban-macro and rural-macro environment with 15 UEs per cell including aerial outdoor users and terrestrial outdoor and inside buildings users with height uniformly distributed between 1.5m and 300m. Among the total UE number, the portion of aerial users is chosen respecting prefixed ratios (e.g. 0%, 0.67%, 25%, ...). For terrestrial users with height up to a threshold, conventional 3GPP channel model are considered, while new channel characterization is introduced between UEs and eNodeBs, to qualify the LOS probability, pathloss, shadow-fading, and fast-fading based on field measurements and ray tracing simulation results contributed by multiple sources.

In [15], the authors studied the feasibility of UAV-assisted networks to enable network coverage extension and capacity enhancement. Measurements were realized to monitor the LTE signals received at the UAV-UE from the ground BSs, to analyze their behavior at different altitudes and hence to assess the signal strength and interference levels. To this aim, the received RSRP levels of the detected LTE signals and the Signal-to-Interference Ratio (SIR). The measurements were performed in 7 different locations, where the total number of potential physical cell ID is 28.

B. Results and Synthesis

Based on the previously stated scenarios, one can summarize that a specific interest on UAVs deployment in LTE networks from several perspectives, with a focus on the 3GPP specifications was presented in [13]-[15], with potential advancement to effectively serve UAVs introduction on the LTE Release 14 functionalities in [13]-[15] and Release 15 in [11]. Figure II-B depicts the evaluation scenarios used in the study carried out by the 3GPP to support the use of UAVs in the Release-15 along with the Inter-Site Distance (ISD), building height, and eNodeB height for each scenario. To characterize the performance of existing cellular networks when serving both ground and aerial devices, the 3GPP defined the following three scenarios

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1) Urban-macro with aerial vehicles (UMa-AV), which represents scenarios where the eNB antennas are mounted above the rooftop levels of surrounding buildings in urban environment;
2) Urban-micro with aerial vehicles (UMi-AV), represents urban scenarios with below rooftop eNB antenna mountings;
3) Rural-macro with aerial vehicles (RMa-AV), which represents larger cells in rural environment with eNB antennas mounted on top of towers;

In UMa-AV, UMi-AV and RMa-AV, aerial vehicles are modeled as outdoor UEs with heights well above ground level (AGL). In the Release-15 study, a maximum height of 300 m AGL was considered for aerial UEs. For performance evaluations, the height of the aerial UEs was assumed to be uniformly distributed between 1.5 m AGL and 300 m AGL. Fixed aerial UE heights of 50, 100, 200, or 300 m AGL were also considered in the study for system level performance evaluations [11].

III. CHANNEL CHARACTERISTIC

We here present the findings of the previously cited works in evaluating the main characteristics of the channel relating aerial devices to the ground networks. Interference and path loss are the main studied aspects in addition to shadowing and fast-fading with slightly less focus. The parameters used to carry out measurements and simulation are summarized in table I.

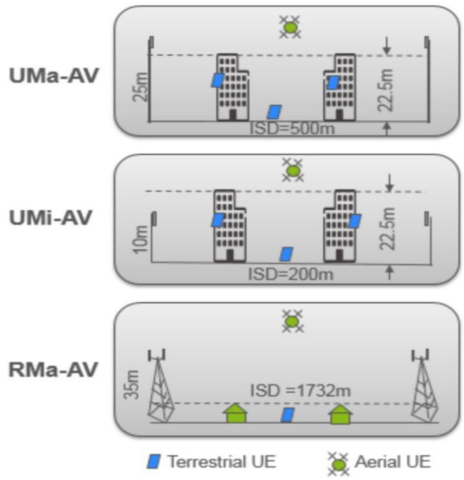

Fig. 2. The evaluation scenarios of channel classification in the Release-15 study on LTE connected UAV: Urban-macro, Urban-micro and Rural-macro communication models [11].

TABLE I
Simulation And Field Measurements Conditions

Ref.	Objective	Environment	Frequency	Altitude	Link type
[10], [11]	evaluation of LOS prob- ability, pathloss, shadow- fading, and fast-fading	urban and rural	2GHz (rural) and 700MHz (urban)	1.5m-300m	UAV-UEs to ground eNB
[12]	evaluation of path loss	rural	800 MHz	20-100m	UAV-UEs to ground eNB
[13]	estimation of LOS proba- bility	rural	700 MHz	1.5m, 40m and 120m	UAV-UEs to ground eNB
[14]	evaluation of path loss, in- terference, and SINR	suburban	800 and 1800 MHz	0-300m	UAV-eNB transmitting in DL or UAV-UEs transmitting in UL
[15]	evaluation of signal strength and Interference	urban	-	0-350m	UAV-UE (relay) to ground eNB

A. LOS and NLOS propagation

LOS propagation is defined as a condition where the direct ray between two points is clear of obstacles. NLOS propagation is a condition where the direct ray between two points is obstructed by obstacles. At a given instant a radio link either has LOS or NLOS [13]. Aerial channel characterization focuses on direct ray tracing status to estimate the LOS probability through simulation. The authors of [13] selected a rural area map in which Base Stations (BSs) and User Equipments (UEs) are randomly dropped, then the LOS or NLOS propagation conditions are determined by examining the eventual presence of blocking buildings or terrain features for different UE heights. The number of dropped BSs is equal to100, placed in different locations not occupied by the buildings at a height of 35 m above the terrain. The results show that even for heights above the BS height of 35m, the LOS probability can be less than 1. Moreover, the LOS probability increases as the 2D distance between two points widens.

The survey presented in [11] reused conventional LOS probability models for aerial UE heights below a lower height threshold (22.5 m for urban scenarios and 10m for rural scenario). In the cases where eBN antenna are above a certain threshold, a 100% LOS probability is assumed for macro cells upper height threshold, while ray tracing simulations is used to determine LOS probability for height range between the lower and upper height thresholds. However, for micro cell, the LOS probability is gradually lower as the height of antennas are below rooftop and ray tracing simulations used to derive a LOS probability model for aerial UE heights above the lower height threshold.

B. Path Loss Modeling

Large-scale path loss is one of the most prominent factors in estimating the received signal power for wireless systems. In [13], large scale pathloss was evaluated through data collected in a helicopter measurement to characterize the channel for mingled LOS and NLOS use cases and compared with the free space and the 3GPP rural macrocell LOS and NLOS pathloss models. The comparison reveals that LOS pathloss is lower bounded by the free-space pathloss at shorter distances, yet at longer ranges increased loss is recorded due to diffraction resulting from the curvature of the earth. Furthermore, for UAV-UEs above 10 m from the ground, the existing 3GPP model would lead to over-estimated pathloss, particularly for UEs at higher altitudes and at large 2D distances. The pathloss measurement carried out in [12] was obtained from the difference between the transmitted power per received symbol (after applying antenna gains) and the Reference Symbol Received Power (RSRP). To assess the impact of the height on radio performance for the UAV, 5 different heights above ground level are considered with a maximum of 100m and a step of 20m with a single route. The log-distance pathloss model is adopted. The main findings of the experimentation carried out in [12] are summarize in the following points:

1) For all flight heights, the path loss exponents are varying between 1.62 and 1.90, which are below free space propagation loss, yet these measurements are slightly biased downwards due to the sensitivity threshold and the penetration losses caused by UAV airframe;
2) The impact of the UAV height on the DL Signal to Interference Noise Ratio (SINR) reveals that as the UAV goes up, the value of the median SINR for the serving cell decreases due to received signal power reduction and the increments in the 3D distances for higher altitude;
3) The disparity in SINR degradation between tested heights shows that the interference increase is more prominent for lower heights, while it is subjected to smaller variation due to height gains at higher levels.

C. Interference

Propagation conditions may be more favorable for UAVs in the sky than for ground users as signals transmitted from aerial vehicles may become visible and cause interference to multiple neighboring BS.

The paper in [14] presents measurements to quantify the interference to the LTE modem as a function of altitude for a 4G LTE network using sports airplane for the range of altitude between 150m and 300m, and a quadrotor UAV between 0 and 120m. It is shown that for UAV-UE, the number of ground base stations identified increases significantly with altitude, and due to line-of-sight propagation conditions, the uplink signal can potentially interfere with many ground UE transmissions in multiple cells. The reference signal received power (RSRP) signal level observed from a hovering UAV to the best ground cell decreases with altitude, but signals from interfering base stations increase because of the elimination of obstacles between the ground eNBs and the aerial UE. The experiments also show that although more cells are detected at higher altitudes, the SINR of the best cell seen at height altitude is lower than the SINR witnessed at ground level. This degradation in SINR is due to interference increase due to the high LOS probability.

In [11], aerial UEs experience LOS propagation conditions to more cells with higher probability than terrestrial UEs, which causes higher UL interference. Consequently, the throughput of terrestrial UEs is degraded resulting in UL resource utilization increase and overall UL performance degradation for both types of UEs. On the other hand, the aerial UEs observe interference from more cells due to the LOS propagation, which causes DL interference, resulting in DL throughput performance degradation of aerial UEs and an increasing DL resource utilization. To manage the interference raised from airborne UEs, the paper presents DL and UL interference detection via UE-based solutions such as measurements of reference signal received power (RSRP), reference signal received quality (RSRQ), reference signal-signal to interference plus noise ratio (RS-SINR) performed at the eNB or reported to it by the UE. Other network-based solutions are possible via the exchange of information between eNBs. These informations can be uplink reference signal configuration of aerial UEs, measurements reported by UE, and DL transmission power. Then, UL power control with UE pathloss compensation, full dimensional multi-input multi-output (FD- MIMO) at the eNB, and directional antennas at UE are suggested for UL interference mitigation while receive beamforming at UE, intra-site Joint Transmission Coordinated Multiple Points (JT COMP) scheme, coverage extension in addition to FD-MIMO and directional antennas at UE.

D. SINR

The paper [12] also examine the factors that can cause the SINR degradation and recap them in three elements. First, the expanded radio horizon of UAV at higher altitudes can add several different sources of interference, potentially adding hundreds of new sources. The second cause is related to the probability of LOS clearing between network transmitters and the UAV-UE is affected by its altitude and strongly depends on the scenario and environment characteristic. In some cases, it might be required to locate the UAV-UE in higher altitude to obtain clearing with neighbor base stations, while in other use cases the altitude need to be adjusted to the tallest rooftops within an area. The third factor appears if the path travelled by the radio signal is partly obstructed, additional losses will occur resulting in an attenuation inversely proportional to the distance between the reflecting surface from the LOS path. The measurement results carried to first evaluate the interference in [14], where then exploited to perform simulation to assess the coverage of a network served partially with aerial base stations located randomly and having LOS propagation with short-term fading. Thanks to their good propagation conditions, even with low output power (10dBm), the UAVs occupied a significant portion of the coverage area which increases with the number of introduced UAVs. However, this increase results in an SINR degradation as the UAV eNBs do cause severe interference to the macrocells and to each other. The SINR evaluated for a scenario in which UAV-UE transmit data to a ground eNB, where UAV-UE is placed directly above the ground UE shows the high sensitivity of SINR to the ground eNB antenna radiation pattern. Indeed, several peaks appear in SINR values due to vertical side lobes while for some altitudes, the SINR values floors as the UE remains under the main lobe of the eNB and the UAV keeps increasing in altitude.
Since the UAV mission in [15] is to act as a flying relay, the backhaul connection must be reliable, thus, the only the cells with RSRP equal to at least -95 dBm are successful. The results showed that, as the UAV flies away from the BSs at higher altitudes, the percentage of the detected RSRP and SIR fluctuate, as the elevation angle changes and as a consequence the sidelobe level and the RSRP also change.

E. Shadow-Fading and Fast-Fading

For all three scenarios defined by the 3GPP in Rel. 15, the same shadow-fading model initially defined for ground network in Rel. 14 are reused for aerial UE heights below a lower height threshold. The lower height threshold is 22.5m for UMa-AV and UMi-AV, while the lower height threshold is 10m for RMa-AV. For higher altitudes, new models were agreed based on field measurements and ray tracing simulation contributed by multiple sources [11]. The standard deviation of the log-normally distributed shadowing gain diminishes for increasing UAV heights, provided that the considered UAV-BS pair is LOS [10]. The overview in [11] also indicated that three alternative fast-fading models that were agreed during the Rel. 15 study. The three alternatives differ in the angular spreads, delay spreads, and K-factor ranges as well as modeling methodology. The first alternative is based on a clustered delay line model, while the second alternative was based on aerial UE height dependent modeling of angular spreads, delay spreads, and K-factor. The third alternative was based on the fast-fading model of Rel.14 with the K-factor set to 15dB.
Other works used fading model inspired by classical existing channels such as Nakagami and Rice. The works in [16], [17] assumed a Rician fading model with K factor depending on the elevation angle through a general non-decreasing function. In order to model the small-scale fading between the UAV and ground UE, the Rician distribution was adopted as an adequate choice due to the possible combination of LoS and multipath scatterers that can be experienced at the receiver side.

The work in [18], also considered Rician model with K factor changes depending on the horizontal displacement of the UAV relative to the ground node (or equivalently, the elevation angle).

In [19], [20], the authors focused on urban communication and used the parameters defined by the International Telecommunication Union (ITU) in its suggestion of a standardized model for urban areas. This latter is characterized by three parameters α to present the ratio of built-up land area to the total land area, β to present the mean number of buildings per unit area, and γ to describes the buildings heights distribution according to Rayleigh probability density function.

IV. CONCLUSION

Due to the rapid growth of consumer UAVs, there has been an increasing activity within the regulation bodies to design and implement new regulations for UAVs to promote safety and privacy. This paper has focused on the recent findings in channel modeling for UAV-Enabled cellular network as part of 5G system. Particularly, we provided a review of experimentation, field measurements and simulations performed to characterize aerial to ground channel. Three main models were pointed out to model the propagation environment of aerial devices, namely Urban-macro for eNB antennas mounted above the rooftop levels of surrounding buildings in urban environment for urban scenarios with below rooftop eNB antenna mountings, and Rural-macro for larger cells in rural environment with eNB antennas mounted on top of towers. From the reviewed research works, we also retrieved the main findings related to the different channels connecting aerial devices to the ground network such as LOS and NLOS propagation, interference, fading, etc. The main aspects that makes LTE networks challenging for serving UAVs connectivity are the coverage and the interference. Indeed, propagation conditions may be more favorable for UAVs in the sky than for ground users. However, as the number of UAVs increases interference management becomes crucial to avoid performance degradation to ground users.

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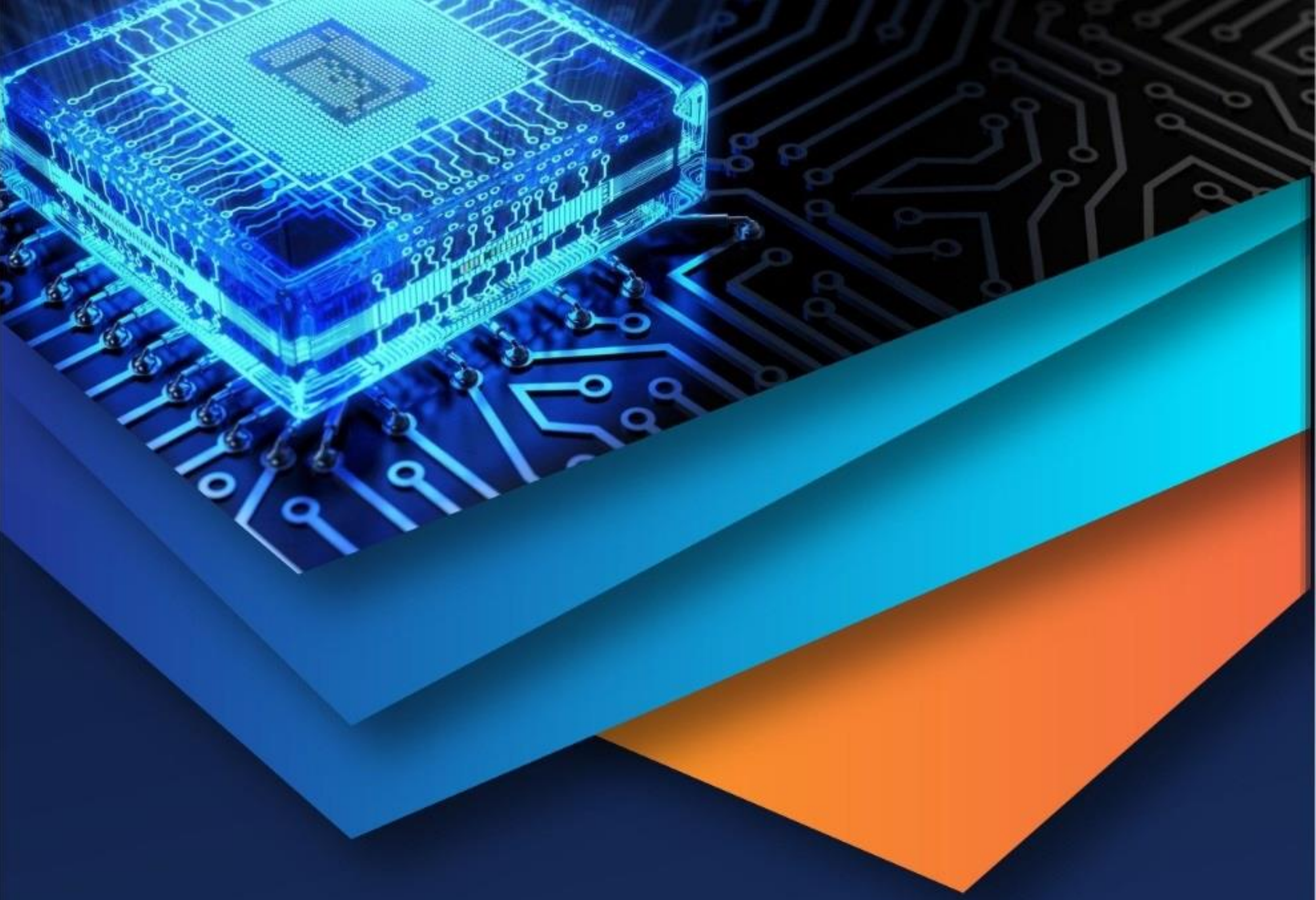

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