iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: VIII Month of publication: August 2026

DOI:

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

Hierarchical Distributed Distortion Aware Beamforming with Dynamic User Association &BS Clustering for Cell-Free Massive-MIMO Systems

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Abstract—Massive multiple-input multiple-output (CF-mMIMO) systems have been identified as a promising technique for wireless communication, in terms of the enhancement of spectral efficiency, network coverage and user fairness. The key issues to be addressed for practical deployment are impairments in the hardware, inter-cell interference, high computational complexity, and high number of backhaul signalling, all of which impact system performance. To tackle these problems, in this paper, a Hierarchical Cluster-Based Distortion-Aware User Association (HC-DA-UA) framework for the distributed CF-mMIMO system under hardware impairments is proposed to solve these problems. The proposed method first clusters the distributed base stations based on the channel energy in a dynamic way to minimize the coordination overhead. Then a hierarchical distributed beamforming method is used to optimise the precoding in each cluster to minimise distortion caused by non-ideal hardware components. In addition, a distortion-aware user association mechanism is used to select the best serving base station for each user, taking into account the signal received and the distortion induced by the hardware and the interference. A second beamforming module called an interference estimation module further enhances the beamforming process to yield the most optimal achievable beamforming signal-to-interference-plus-noise-and-distortion ratio (SINDR). The simulation results reveal that the proposed HC-DA-UA framework always outperforms the existing counterparts in terms of sum-rate, whilst substantially decreasing the computational complexity and signalling overhead, thus it is an efficient and scalable solution for next-generation hardware-impaired distributed wireless communication networks.
Keywords— Cell-Free Massive MIMO, Distributed Beamforming, Dynamic Clustering, Hierarchical Beamforming, Distortion-Aware User Association, Hardware Impairments, Signal-to-Interference-plus-Noise-and-Distortion Ratio (SINDR), Backhaul Overhead, Computational Complexity, Spectral Efficiency, Wireless Communications, MATLAB Simulation.

I. INTRODUCTION

Fifth-generation (5G) and sixth-generation (6G) Wireless Communication Systems have brought a new set of requirements for high data rates, huge connectivity, smallinactivity, and spectral & energy efficiency. But conventional cellular networks are limited in terms of inter-cell interference, coverage and user performance and hence cannot meet the requirement of future wireless applications[1], [2].

Massive multi-input multi-output (MIMO) is a promising technology for spatial multiplexing and beamforming which is used to improve wireless system performance. With the help of a massive number of antennas, massive MIMO enhances spectral efficiency, system capacity and the reliability of communication. However, interference caused by the cell edge and scalability limitations are still issues in centralized massive MIMO systems[3].

To overcome these difficulties, a distributed communication system, in which multiple access points located in different locations share users without any specific cell boundaries. This design provides more coverage, fairness to users, and spectral efficiency and minimizes inter-cell interference, which makes it a viable skill for outside 5G and 6G wireless systems[2], [4] and [5].

However, its benefits are offset by issues related to hardware impairments, computational complexity, backhaul overhead, and efficient user association, among others, for practical deployment of CF-mMIMO. Furthermore, a centralized beamforming approach necessitates a high amount of information sharing between the distributed access points which translates to a high level of processing complexity and signaling overhead [1], [4].

Based on the above problems, a Hierarchical Cluster-based Distortion-Aware User Association (HC-DA-UA) method is proposed for hardware-impaired CF-mMIMO.

The proposed method combines dynamic clustering, hierarchical beamforming and distortion-aware user association to increase the performance of the network and decrease the computations and backhaul overhead. The MATLAB simulation results show that the proposed architecture can outperform the conventional Ring, Star, Centralized and Distortion-Aware User Association (DA-UA) schemes, it is a scalable and efficient solution in next-generation distributed wireless communication networks.

II. RELATED WORK

The use of massive multiple-input multiple-output (MIMO) is one of the crucial technological foundations of current wireless communication systems as it can greatly increase spectral efficiency, network capacity and energy efficiency. With the evolution of wireless networks towards 6th generation (6G) systems, the researchers have extended massive MIMO into tremendouslyimportant MIMO (XL-MIMO) with very large antenna arrays capable of higher spatial resolution and enable near-field communication. In recent years, surveys have been conducted extensively to cover the architectures of XL-MIMO, channel models, electromagnetic properties, signal processing methods, and low complexity beamforming algorithms, and also pointed out that deep learning is a potential solution in practice. Scalable beamforming and distributed optimization of the beamformer under practical hardware limitations, however, are still important research challenges [6], [7].

The concept of beamforming is the key to an effective realization of the potential of massive MIMO systems. The conventional fully digital beamforming gives good performance, but is costly and consumes power since the amount of dedicated radio-frequency cables required is equivalent to the number of antennas. Hence an efficient alternative using hybrid analog-digital beamforming has developed for large antenna arrays. Conventional mathematical optimization methods, artificial intelligence-based beamforming methods such as deep learning and deep unfolding methods have been investigated recently. At the same time, millimeter-wave (mmWave) communications have been extensively investigated in conjunction with hybrid beamforming due to its ability to take advantage of the large bandwidths for high-data-rate transmission. However, these techniques suffer from some drawbacks, such as beam alignment, propagation loss, complexity of the hardware, and computational expense, that prohibit their practical implementation[6][8][9].

Conventional cellular architectures are facing many challenges, making cell-free massive MIMO (CF-mMIMO) a distributed model of communication technology with much attention. CF-mMIMO aims to enhance network coverage, user fairness and interference management by serving users with geographically distributed access points (APs). The channel estimation, precoding, receive combining, resource allocation and fronthaul design, scalability, and distributed signal processing techniques have been discussed in existing surveys in detail. While these studies illustrate the tremendous benefits that can be obtained from CF-mMIMO, efficient distributed beamforming and scalable user association still represent interesting open research challenges in the context of a large base station deployment[6].

There has been more newinvestigation on the possible combination of CF-mMIMO with a number of new technologies to improve network performance. To realize programmable electromagnetic environments, continuous aperture antennas and intelligent beamforming has been introduced as Holographic MIMO (HMIMO). Likewise, full-duplex communication, intelligent reflecting surfaces (IRS), and non-orthogonal multiple access (NOMA) have been integrated with CF-mMIMO to enhance the spectral efficiency, energy efficiency, connectivity and interference mitigation. These fully integrated systems provide significant theoretical benefits, but also pose new implementation issues of hardware impairments, distributed optimization, beamforming complexity, and practical implementation[7].

It can be seen from the literature that most of the research works are targeted to the perspective of one aspect of the wireless communication system, either hybrid beamforming, XL-MIMO, intelligent reflecting surface, or user-centric CF-mMIMO. Works that consider multiple key challenges such as dynamic clustering, hierarchical distributed beamforming, distortion-aware user association, hardware impairments, computational complexity, and backhaul overhead in a unified framework are much less common in comparison. This work proposes a Hierarchical Cluster Based Distortion-Aware User Association (HC-DA-UA) framework which combines dynamic clustering and hierarchical beamforming with distortion-aware user association to enhance the achievable sum-rate performance while reducing the computational complexity and backhaul signaling in the distributed cell-free massive MIMO systems.

III. SYSTEM MODEL

We consider a distributed cell-free massive multiple-input multiple-output (CF-mMIMO) system with B base stations (BS_s) that are geographically distributed and each has $N_t$communicateprojections and assists K handlers with only a solitary antenna.

In contrast to traditional cellular networks, BS_s work together to provide their users without any fixed boundaries, and therefore, they can achieve better spectral efficiency and interference between cells is minimized.

Assume that there is a networkamongst the b^{th} BS and the users denoted by a matrix H_b, which has size of $C^{(N_t \times K)}$. The communicated signal from b^{th} BS is assumed by

$$x_b = W_b s \qquad (1)$$

where

- W_b is the beamforming matrix,
- s is the communicated symbol vector satisfying

A. Hardware Impairment Model

The transmitter hardware has nonlinear distortion in practical wireless system because of the imperfection of the radio-frequency components. The channel is represented by an effective transmit gain matrix:

$$G_b = \beta_1 + 2\beta_3 diag\left(diag(W_b W_b^H)\right) \qquad (2)$$

where

- β_1 represents the linear gain coefficient,
- β_3 denotes the third-order nonlinear distortion coefficient.

B. Signal-to-Interference-plus-Noise-and-Distortion Ratio

The acknowledged signal at the k^{th} user is equal to the anticipated signal, multi-handler interference, hardware distortion and additive white Gaussian noise. Thus, the Signal-to-Interference-plus-Noise-and-Distortion Ratio (SINDR) is defined as:

$$SINDR_k = \frac{S_k}{I_k + D_k + \sigma^2} \qquad (3)$$

where

- $S_k$is the looked-for signal power,
- I_k is the interference power,
- D_k is the hardware distortion power,
- σ^2 is the noise variance.

C. Achievable Sum Rate

Shannon's capacity theorem is used to get the reachable network sum rate, which is given by

$$R_{sum} = \sum_{k=1}^{k} log_2 (1 + \gamma_k) \qquad (4)$$

D. Distributed Communication Framework

The distributed BS_s are partitioned into several clusters of BS_s that are able to cooperate with each other, with the aim of making the system scalable and reduce the computational complexity. The optimization of beamforming and user association is conducted in each cluster considering channel conditions, hardware impairments and inter-cluster interference.

$$W_c^* = arg\ max_{W_c} \sum_{k \in U_c} log_2 (1 + SINDR_k) \qquad (5)$$

In the next section, the detailed dynamic clustering strategy, the hierarchical beam forming optimization and distortion aware user association mechanism are described.

IV. PROPOSED METHOD

To address the above challenges, this paper presents a Hierarchical Cluster-Based Distortion-Aware User Association (HC-DA-UA) framework which enhances the presentation of the hardware-limited cell-free massive MIMO.

The proposed framework is designed to maximize the achievable sum rate while minimizing the complexity and the backhaul overhead by implementing dynamic clustering, hierarchical beamforming, distortion-aware user association, and interference-aware optimization. The entire workflow can be divided into 5 stages, which are described below.The proposed Framework is summarized in a flowchart in figure 1.

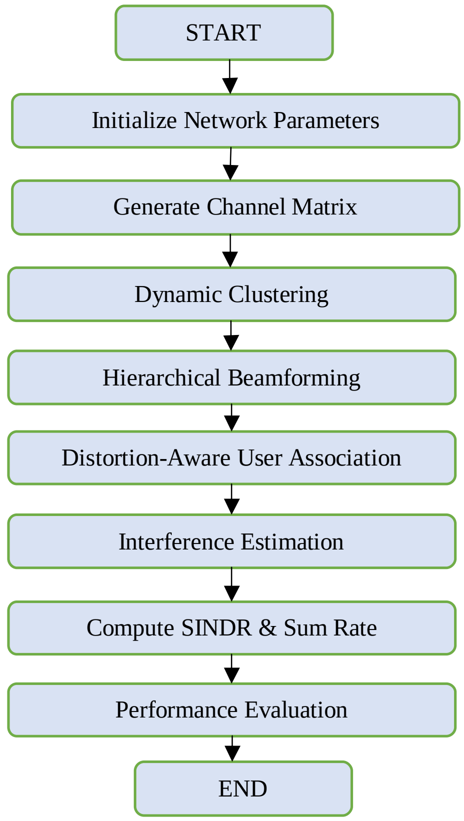

Figure 1:Flowchart of the proposed Framework

A. Dynamic Clustering

The first stage is for clustering of the distributed base stations into multiple cooperative base stations clusters based on channel conditions. The proposed framework selects a cluster dynamically from the base stations which have similar channel characteristics instead of using fixed clusters, so that the cluster structure changes according to the change of the network condition.

This approach makes it easier to achieve coordination among all base stations, and allows for local processing, which increases scalability and decreases computational load.

B. Hierarchical Beamforming

After the clusters are created, the optimization of the beamforming is conducted in a hierarchical fashion in each cluster. Instead of optimizing the beamforming vectors for all the distributed base stations, each cluster optimizes its own beamforming vectors using local channel information.

The information for optimized beamforming is then shared between clusters in order to enhance overall network performance. It's a hierarchically optimised method which decreases the processing complexity of the system, thus keeping interference suppression and signal enhancement efficient even as the resolution is reduced.

C. Distortion-Aware User Association

Optimization of the beamforming is performed and user are associated with the most suitable base-stations. The proposed method takes channel quality, hardware-induced distortion and beamforming performance into account simultaneously for the association process, different to the conventional association methods based on received signal strength.

Consequently, users are now on connection with base station operating in the environment that is more reliable in terms of communication and the quality of the signal transmission under practical hardware impairments.

D. Interference Estimation

The proposed framework also calculates the interference caused by the base station's adjacent base stations in every optimization step to further improve the transmission performance.

Each cluster is allowed to reduce the inter-cluster interference while maintaining the power of the desired signal in its updating process using the estimated inter-cluster interference. The interference-aware optimization helps increase the reliability of communications and optimizes radio resources.

E. SINDR Computation

Lastly, Signal-to-Interference-plus-Noise-and-Distortion Ratio (SINDR) is used to assess the communication performance. The computed SINDR combines the impact of the chosen signal strength, multi-handler interference, hardware distortion and background noise.

The network sum rate that can be achieved based on the SINDR values obtained is calculated and used to evaluate the effectiveness of the proposed HC-DA-UA mechanism. The optimization process is then repeated until convergence, leading to higher spectral efficiency, reduced computational complexity and decreased amount of backhaul signalling compared to the conventional distributed beamforming solutions.

V. RESULTS

A. Sum Rate vs Iteration

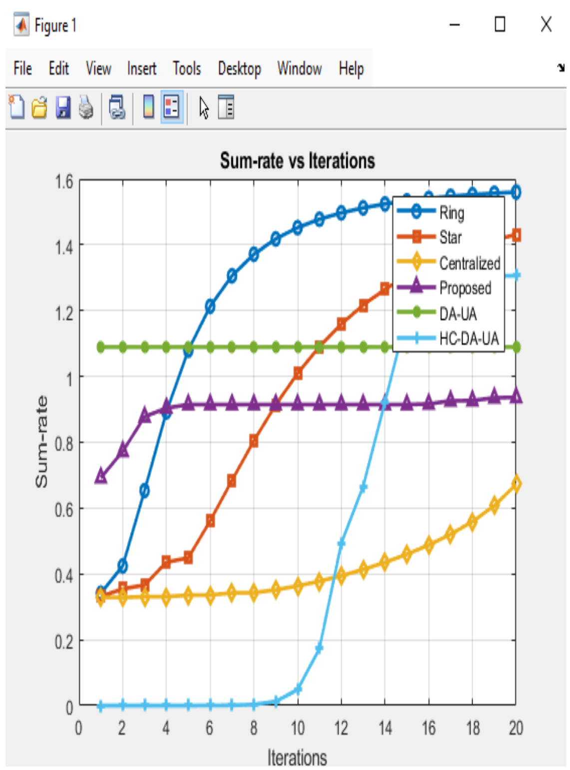

Figure 2:Sum Rate vs Iteration

The HC-DA-UA scheme is compared with Ring, Star, Centralized and DA-UA scheme and it is observed that the proposed HC-DA-UA scheme shows the convergence behaviour as shown in Figure 2. The projected framework is able to reach a higher sum rate in a lesser number of iterations thanks to its hierarchical beamforming and dynamic clustering strategy.

The convergence curve is used to show the stability and effectiveness of the proposed optimization process.

B. Sum Rate vs. Transmit Power

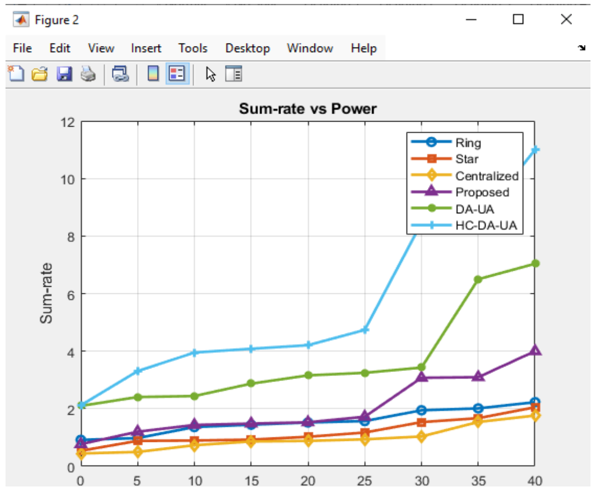

Figure 3:Sum Rate versus Transmit Power

Figure 3proves the summation rate that can be achieved for various transmit power levels. The sum rate of all the methods improves with cumulative transmit power, but the HC-DA-UA achieves the highest sum rate at all the transmit power levels. The efficient distortion-aware user association and hierarchical beamforming are the main reasons for this improvement, as they can effectively reduce hardware impairments and interference.

The more the sum of base stations, the morethe sum rate.

C. Sum Rate vs. Number of Base Stations

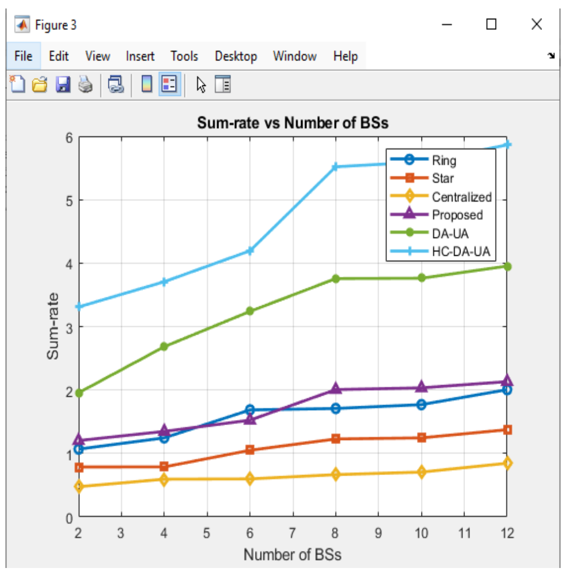

Figure 4:Sum Rate vs. Number of Base Stations

Figure 4demonstrations the performance of the network with diverse number of distributed base stations. With a larger number of base stations, the sum rate would increase because of increased spatial diversity and better connectivity of users. The proposed HC-DA-UA framework is shown to be more scalable in that it can effectively utilize extra base stations, and yet has minimal coordination overhead.

The more the antennae the stronger the signal.

D. Sum Rate vs. Number of Antennas

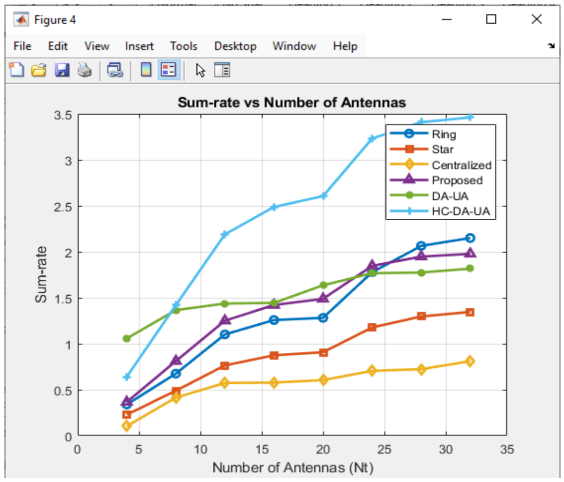

Figure 5:Sum Rate vs. Number of Antennas

TheFigure 5demonstrates the variation of achieved totality rate with sum of transmit antennas. The higher the number of antennas the better the beamforming capability and spatial multiplexing gain, which gives higher throughput. The proposed framework shows superior performance over all other methods, by optimising the hierarchical beamforming in the amount of additional antenna resources.

E. Computational Complexity

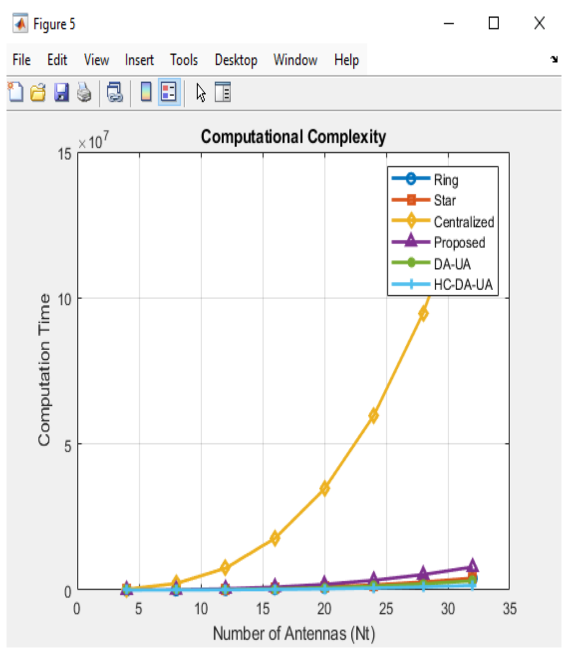

Figure 6:Computational Complexity

The computational difficulty of the HC-DA-UA framework is compared with the benchmark schemes in Figure 6. The proposed method is less computational intensive since optimizing a beamforming is done in a dynamically formed cluster rather than the whole network. This optimization of the data processing is localized, thus significantly reducing processing overhead without compromising the communication performance.

F. Backhaul Overhead

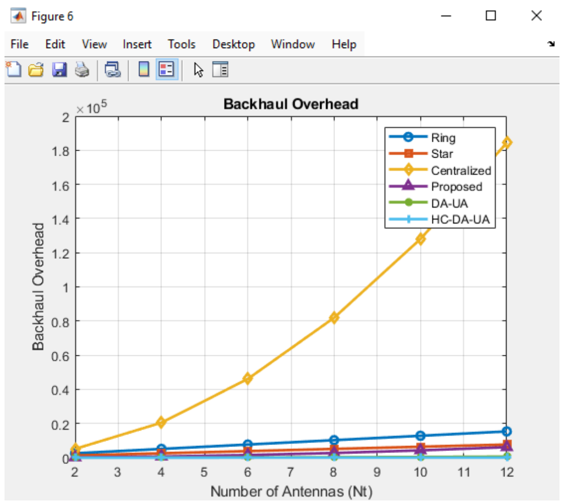

Figure 7:Backhaul Overhead

The comparison of backhaul signalling overhead of different communication frameworks are shown in Figure 7. The proposed HC-DA-UA framework has the lowest backhaul overhead due to the fact that it optimizes communication between distributed base stations to a minimum level by forming clusters. This reduction in signalling will facilitate scaling up, and make the proposed framework more practical and viable for large-scale cell-free massive MIMO placements.

VI. CONCLUSION

The paper introduced a Hierarchical Cluster-Based Distortion-Aware User Association (HC-DA-UA) for hardware-impaired cell-free massive MIMO (CFmnMIMO) system. The proposed framework combines dynamic clustering, hierarchical beamforming, distortion aware user association with interference estimation to enhance network performance with low computational complexity and backhaul overheads. The proposed method can effectively reduce the interference and hardware-induced distortion, improving the reliability and scalability of communication by performing optimized operations in a cooperative cluster at the local level. The simulation results using MATLAB confirmed that the HC-DA-UA framework consistently achieves higher sum rate when compared to conventional Ring, Star, Centralized and Distortion-Aware User Association (DA-UA) schemes in terms of computational effectiveness, signalling overhead and sum rate. Based on the obtained outcomes, the proposed framework is efficient and scalable solution for next generation distributed wireless communication network.

In the future, the proposed HC-DA-UA will be expanded to other more practical and dynamic wireless communication scenarios. The framework can be improved with AI and RL techniques for time-varying environments with adaptive beamforming and user association. Also, the use of intelligent reflecting surfaces (IRS), reconfigurable intelligent surfaces (RIS), non orthogonal multiple access (NOMA) and XL-MIMO may be investigated to further enhance the spectral and energy efficiencies. The proposed framework can also be tested against user mobility, imperfect channel state information, heterogeneous network deployment, and hardware impairment models of realistic hardware impairments to ensure the robustness of 6G wireless communication systems.

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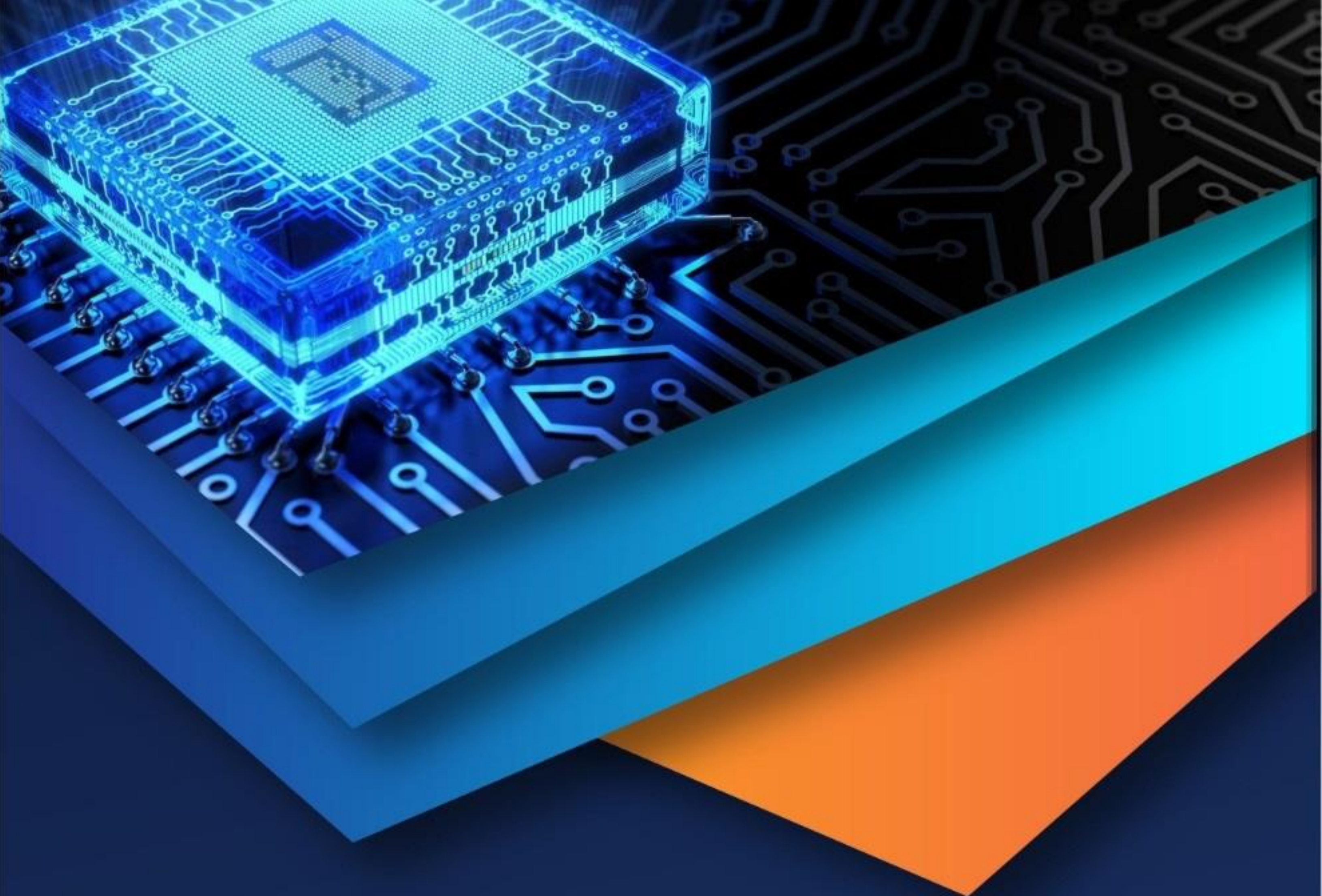

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