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A Review of LoRa and LoRaWAN Technologies for IoT Applications

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Abstract: ***This analysis undertakes a thorough review of LoRa and LoRaWAN technologies as they apply to Internet of Things contexts. This review offers a structured comparative study of performance metrics across various deployment scenarios, covering urban, rural, and forested environments. The investigation covers essential parameters, including spreading factor, bandwidth, coding rate, energy consumption, and network scalability. It assesses recent development in areas such as energy optimization, adaptive data rate mechanisms, and AI-driven approaches to network management. Focusing on the comprehensive literature review, this study identifies notable research gaps and proposes possible ways for future research, mainly involving hybrid network architectures, the integration of edge intelligence, and cross-layer optimization strategies.***
Keywords: LoRa, LoRaWAN, Low Power Wide Area Network (LPWAN), Chirp Spread Spectrum (CSS), Adaptive Data Rate

I. INTRODUCTION

The Internet of Things (IoT) represents a fundamental concept in modern communication systems, enabling large-scale interconnection of devices across various application [22]. These applications extend from urban and industrial environments to rural areas, for healthcare monitoring and environmental sensing [1, 3]. The rapid expansion of IoT has increased the demand for communication technologies that support long-range connectivity, low power consumption, and scalable network deployment.

Usual wireless communication technologies such as Wi-Fi, Bluetooth, and ZigBee are effective for short- range applications; however, their limited coverage and relatively high energy consumption confine their suitability for large-scale IoT deployments [5, 6]. Consequently, Low Power Wide Area Networks (LPWANs) have appeared as a practical solution to address these limitations. Among these, LoRa (Long Range) employs Chirp Spread Spectrum (CSS) modulation, enabling robust communication even under low signal-to-noise conditions [5, 22]. The corresponding network protocol, LoRaWAN, utilizes a star-of-stars topology in which end devices communicate with gateways connected to centralized network servers, enabling long-distance communication with minimal energy requirements [5, 15].

Researched studies have tested that LoRa-based systems can achieve communication range of up to 15 km in rural environments and a couple kilometers in urban areas, depending on deployment conditions and environmental factors [4, 13]. Extensive research has evaluated their performance across various scenarios, including urban, forest, and rural environments, as well as application domains such as healthcare monitoring, asset tracking, emergency communication, and smart city systems [1, 3, 4, 8, 11, 19]. These studies primarily focus on improving energy efficiency, optimizing transmission parameters, and reducing interference to improve network scalability and reliability [5, 7, 12, 15, 20].

Despite these advancements, several challenges remain, that includes network congestion, limited data rates, and performance degradation in complex or obstructed environments. Furthermore, existing studies often address these challenges independently, resulting in a lack of integrated analysis that combines performance evaluation, network limitations, and emerging intelligent optimization techniques. This paper addresses this gap by presenting a structured and comparative review of LoRa and LoRaWAN systems. The objective is to provide a comprehensive understanding of the compromises between communication range, power consumption, and data rate, while identifying future research directions for IoT communication systems.

II. OVERVIEW OF LORA AND LORAWAN

A. Lora Physical Layer

LoRa (Long Range) is a registered modulation scheme by Semtech which utilizes principles of Chirp Spread Spectrum modulation [5, 6]. In CSS modulation, a chirp signal which changes frequency over time is used to encode the information and allows for robust communication in conditions of very low signal-to-noise ratios. It is resilient to noise, Doppler frequency shift and multipath propagation making it good for long-range, low- power wireless systems. Experiments shows that it is possible to receive the information below the noise floor for LoRa system with up to 16 dB of processing gain [5, 6].

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LoRa works within unlicensed Industrial, Scientific, and medical frequency bands, namely 433 MHz, 868 MHz and 915 MHz based on regions. When operating under typical conditions, LoRa provides communications up to 15 km away from the receiver (rural) or 2-5 km (urban) with low power output levels (2-20 dBm) [1, 4, 13].

The performance factors in LoRa are characterized by three adjustable parameters, Spreading Factor, Bandwidth and Coding Rate [5, 20]. Spreading Factor specifies how many symbols are used to represent each data bit; a higher spreading factor means that data is spread over a larger symbol length allowing greater receiver sensitivity and greater link budget, at the expense of lower data rate and a longer transmission time. Bandwidth represents the width of the frequency spectrum occupied by the signal; increasing the bandwidth increases the data rate while it reduces the link budget. Coding Rate refers to the amount of redundancy added to each symbol, which increases link reliability under poor channel conditions at the cost of increased transmission overhead.

These parameters make compromises between range, power consumption and data throughput, and therefore, LoRa is suitable for IoT systems such as environmental monitoring, asset tracking, and low power sensors [3, 11, 17, 19].

B. LoRaWAN Network Architecture

LoRaWAN specifies the MAC and network layer protocol situated over the LoRa physical layer. The topology is based on star-of-stars and end nodes send data directly to one or more gateways using LoRa modulation [5]. The gateway, upon receiving the data, relays it over IP-based backhaul to a centralized network server. The network server handles device authentication, packet duplication and Adaptive Data Rate management while application servers manage and visualizes the data [5, 15].

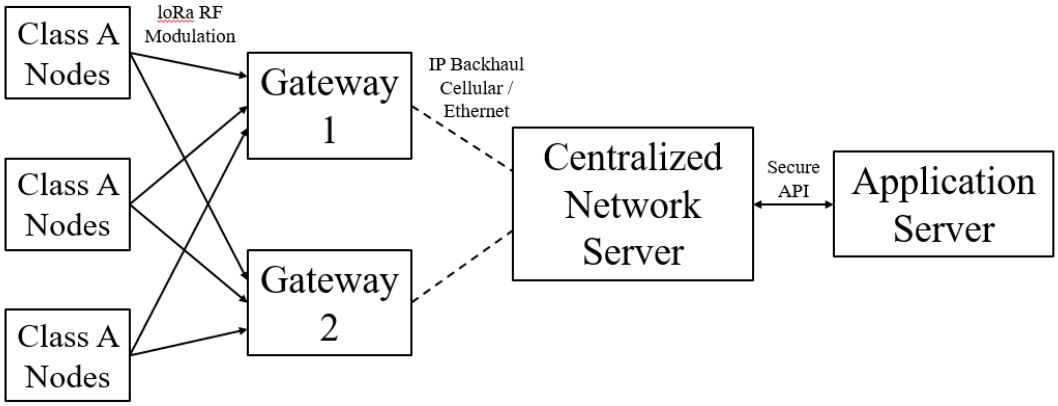

Fig. 1 hardcopy LoRaWAN Network Architecture

Class A: Enables two-way communication with low power consumption; devices open receive windows only after sending uplink messages.

Class B: Supports scheduled receive windows, allowing predictable downlink communication.

Class C: Provides almost constant receive windows, resulting in low latency, but at the cost of higher power consumption.

In the LoRaWAN architecture as seen on Fig. 1, end nodes are directly connected to gateways, and gateways are connected to the network server. This architecture can handle a large number of end devices at a central location and uses less energy.

This protocol is suited for wide area deployment. A number of devices can be connected to one gateway. The number of devices depends on factors such as traffic volume, limitations of duty-cycle, channel availability, etc. [15, 16].

C. LoRa's technical characteristics and performance

LoRa and LoRaWAN systems has many vital features. LoRa has low power consumption level, good scalability and a long range of communication. End devices can operate for several years on standard batteries due to efficient duty-cycling and low transmission requirements.

As for security, LoRaWAN supports AES-128 encryption in network and application level, providing security from the end-to-end device. However, these strengths lead to some weaknesses. A disadvantage of LoRaWAN is that it has relatively low data rates, approximately in between 0.3-50 Kb/s, which can be a limitation for applications that must deliver high bandwidth. Moreover, the duty-cycle limit and the usage of an ALOHA-like access mechanism may lead to an increased packet collisions and delays when used in congested environments [5, 15, 16].

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III.REVIEW OF RESEARCH ON LORA COMMUNICATION

A. Hardware and Modulation Techniques

The performance and reliability of the system with the usage of the LoRa module highly depends on the hardware used, as well as the features of the physical layer modulation scheme. It is observed that majority of the LoRa based systems make use of sub-GHz ISM band transceivers which can be configured based on several parameters [5, 6, 20].

Various implementations experimented in literature demonstrate the practical usability of the LoRa hardware and modulation. LoRa based communication systems has the capability to carry out real time data exchange in low signal to noise conditions whereas a comparative study with other technologies such as XBee concluded LoRa superior in terms of packet delivery ratio and communication range in mobile and outdoor environment [1, 2, 4, 13].

Integration of LoRa with embedded platforms such as Arduino, Raspberry Pi and GPS module has been showed that support application such as tracking, and sensing based on edge processing [3, 11, 17]. Low power and cost effective IoT systems have been demonstrated with commercial hardware.

$$R_s = \frac{BW}{2^{SF}}$$

From a modulation perspective, the CSS based LoRa has more benefits compared to traditional FSK due to improved coverage. More spreading factors give more sensitive receiver and long communication range but increases symbol duration which will decrease the data throughput [5, 6]. Therefore, tuning of these parameters has to be done based on different applications and surroundings.

B. Performance And Range Studies

LoRa system performance and range are affected by various factors such as the environment, the network settings and the transmission settings. The usual metrics that are used to evaluate the performance of a LoRa system are the received signal strength indicator, the signal-to-noise ratio, the packet delivery ratio and the time on air [1, 4, 13, 17, 19].

In densely populated cities, environmental factors such as multi-path effects and obstacle caused by buildings have an impact on signal propagation. Experimental results shown that the communication range is reliable limited to about 1 km while density of the obstacles increased on line-of-sight [13]. The installation of gateways also affects to be important because it intensifies the utility of overhead lines.

In comparison, open rural and outdoor environments demonstrate the advantages of LoRa communication. Several kilometres can be achieved with the experimental measurements, and the coverage relies on the geography and the infrastructure available at a certain location. Measurements made in rural environment reveals that by using relay nodes or the optimal positioning of gateways, the coverage can be increased [1]. On the other hand, the forestation can increase the attenuation from the signal significantly, therefore decreasing the communication range [4].

The LoRa technology has been studied in mobile and application-specific contexts. The comparison between LoRa and short-range solutions, like XBee, has shown that LoRa delivers more robust communication in a more hostile environment at longer distances [2]. Likewise, the GPS tracker achieved consistent communication against the static reference in a suburban environment, even though with a shorter range, Obstacles and attenuation [3, 17].

Transmission settings play a significant role in communication performance in all the use cases. [5, 15, 20].

The works analysed shows LoRa providing long range communication reliably, but in complex scenarios, the performance is limited by physical obstacles, interference and trade-offs between configurable parameters.

C. Network And Protocol Challenges

Despite the advantages of LoRa and LoRaWAN, there are several issues that challenge the scalability and reliability of the network, especially for densified internet of things (IoT) deployments. These challenges mainly arise from duty-cycle limitations, channel access mechanisms, interference, and adaptive parameter control.

LoRaWAN utilizes unlicensed frequency bands and has severe duty-cycle limitations that restricts the frequency of transmissions and packet size [15]. In large scale networks, the limitation causes packet collision and transmission delay. Adaptive scheduling mechanism, such as Improved Environmental Adaptation Method (IEAM), has been suggested to adaptively determined optimal transmission time according to environmental needs that results a 61% reduction in response time and 36% efficiency gain in energy [12].

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Interference and collision management remain serious concerns due to the use of an ALOHA-based medium access scheme, which does not perform channel sensing before transmission [15]. The more nodes are integrated to the network, the more colliding packets occur, and this leads to reduction of the Packet Delivery Ratio (PDR). Adaptive spreading factor allocation and optimization algorithms, helps handle this phenomenon but are limited by coordination between distributed devices.

The dynamic data rate (ADR) adjusts the transmission parameters such as the spreading factor and power setting. While it is effective for stationary infrastructure, it performs poorly in mobile or dynamic conditions while allowing less optimal performance. In addition, the network scalability is limited by the gateway's capacity such that single channel gateways can be bottlenecks in high traffic scenarios [20].

We conclude that achieving optimized performance in LoRa network necessitates various research issues, which include interference mitigation, adaptive routing, spectrum efficiency and security aspects.

D. Energy And Optimization Techniques

The energy saving characteristic is a necessary feature that has to be considered for utilization of LoRa based IOT systems as the majority of end devices run on limited battery sources. Though the physical layer maintains naturally low power communications, additional optimization on network and system level is needed.

Recent investigations concentrated on adaptive scheduling/routing schemes for energy saving. In this context IEAM [12, 16, 20], extend the communication scheduling dynamically according to the environment, and accomplish improvements on energy performance and delay time of communications relative to the traditional optimization schemes.

Further energy conservation can be achieved through hardware level optimization. For example, microcontrollers provide deep-sleep modes, enabling the nodes to be dormant between two packets, greatly increasing lifetime. Several low-cost energy efficient implementations have been developed and validated for real-world GPS-tracking systems [3, 17].

According to comparative studies, LoRa appears to be the most suitable choice for balancing low power consumption, long range and system flexibility in contrast to the other alternative LPWAN technologies. It offers more comprehensive features than Sigfox, meanwhile consumes less power than NB-IoT even with a higher data rate [5, 15, 16, 20].

E. IoT Applications

Both LoRa and LoRaWAN are used in many application areas of IoT. This is mainly attributed to a number of advantages which both the protocols provide including low power consumption, long communication distance, and low cost.

In the medical field, physiological parameters including pulse rate, body temperature and oxygen level have been remotely supervised with a LoRa-based system, which shows that the low-data-rate medical telemetry can be implemented with a very high reliability [3]. With existing GPS module, location tracking system is a popular application that asset and vehicle can be monitored efficiently. The results show that the data transmission is relatively stable in suburb area even with the constraint of range due to obstacles [11, 17]. LoRa has been employed in communications systems that do not require internet infrastructure. These systems allow remote peer-to-peer messaging and emergency communication in the event of a disaster [14]. LoRa has also been used in hybrid communication systems in the transportation and industrial sectors where LoRa is used for long range telemetry and other short-range technologies are used for local messages [2, 9]. These applications demonstrate the versatility of LoRa in supporting low-power, long-range communication across multiple domains. However, application performance remains dependent on environmental conditions, network configuration, and system-level optimization strategies.

IV. COMPARATIVE DISCUSSION AND ANALYSIS

LoRa and LoRaWAN are widely recognized as effective solutions for wide-area IoT communication, offering a balance between communication range, energy efficiency, and deployment simplicity [2, 3, 8, 16]. However, it is influenced by environmental conditions, network configuration, and application-specific requirements, leading to inherent comparison in performance [4, 7, 10].

A. Performance Across Environments

LoRa's performance can change according to the surrounding environment. Details like the terrain profile, the obstacle density, the location of the LoRa gateways is crucial to a reliable performance [1, 4]. It has been studied that gateway height and antenna placement can have a major effect on the signal behaviour [1, 4]. For instance, when using high gateways, there is a more reliable line-of-sight of the signal and higher coverage, while when employing low height equipment in cities there are discontinuities and attenuation in the signal coverage [3].

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Although LoRa provides a better communication range over short range technologies, it is sensitive to environment variations as well. Relay nodes or multi-gateway solutions guarantee a more reliable communication in a blocked or moving environment, increasing the coverage and lowering down the effects of signal decay [5, 9, 10, 14].

B. Energy Efficiency and Power Consumption

Energy efficiency is a key advantage of LoRa technology, enabling long-term operation of battery-powered IoT devices. Typical deployments achieve extended operational lifetimes through efficient duty-cycling and low transmission power requirements [12, 20].

In comparison with other LPWAN technologies, LoRa provides a balanced Comparison between power efficiency and functionality. NB-IoT offers higher data rates but at the cost of increased energy consumption due to its reliance on cellular infrastructure, while Sigfox achieves very low power usage with limited payload capacity and communication flexibility. Consequently, LoRa occupies an intermediate position, offering moderate data rates with efficient energy utilization and deployment flexibility [2, 10, 16, 17].

C. Data Rate, Latency, And Throughput

LoRa systems operate at low data rates, typically ranging from 0.3 kbps to 50 kbps, depending on transmission parameters [3, 7]. While sufficient for periodic sensor data transmission, these limitations restrict the applicability of LoRa in latency-sensitive or high-throughput applications.

Higher spreading factors improve communication range and reliability but increase Time on Air (ToA), resulting in reduced throughput and increased latency [5, 18]. Adaptive Data Rate (ADR) mechanisms partially address these trade-offs by adjusting transmission parameters. However, their performance is limited in mobile or rapidly changing environments, where delayed adaptation can lead to temporary performance degradation and increased energy consumption [1, 19].

D. Comparative Overview with Other Technologies

Compared to short-range communication technologies, LoRa offers significantly greater communication range and lower power consumption at the expense of reduced data rate [5, 10]. ZigBee supports high data throughput and mesh networking but is limited by short communication distances and higher energy requirements.

TABLE I
COMPARISON OF WIRELESS COMMUNICATION TECHNOLOGIES

Technology	Operating Frequency	Range	Data Rate	Infrastructure Requirement	Power Efficiency
LoRaWAN	433 / 868 / 915 MHz	Up to 15 km	0.3–50 kbps	Gateway + Network Server	Excellent
Sigfox	868 / 915 MHz	10–50 km	Up to 100 bps	Sigfox Base Stations	Very High
NB-IoT	Licensed LTE Bands	1–10 km	Up to 250 kbps	Cellular Infrastructure	Moderate
Weightless-P	Sub-GHz	Up to 5 km	Up to 100 kbps	Base Station	High
ZigBee	2.4 GHz	10–100 m	Up to 250 kbps	Local Coordinator	High
LongBee	868 / 915 MHz	1–2 km	Up to 250 kbps	Local Infrastructure	Good

LongBee extends ZigBee capabilities through sub-GHz operation but does not achieve the long-range performance of LoRa in open environments [4, 19]. Among LPWAN technologies, Sigfox provides extended range with low energy consumption but limits communication flexibility, while NB-IoT offers reliable connectivity with higher operational costs and energy usage due to its dependence on cellular networks. Weightless-P remains less widely adopted and largely experimental [2, 8, 13].

E. Application-Level Insights

LoRa demonstrates effectiveness across a wide range of IoT applications, including healthcare monitoring, environmental sensing, asset tracking, industrial telemetry, and defence communication [1, 7, 10, 20]. It provides reliable communication under low power constraints making it particularly suitable for large-scale, distributed sensing applications.

Experimental studies indicate consistent performance in applications requiring periodic data transmission, while maintaining robustness in both static and mobile scenarios. However, application performance remains dependent on environmental conditions, network design, and system-level optimization.

V. CONCLUSION

LoRa and LoRaWAN represent main technologies in the LPWAN system, providing long-range, low-power, and scalable communication for IoT applications. Their use of Chirp Spread Spectrum (CSS) and adaptive mechanisms such as ADR enables reliable operation under controlled conditions, making them suitable for large-scale, energy-efficient deployments.

This review highlights that, despite these advantages, challenges such as low data rates, network congestion, duty-cycle constraints, and security limitations remain significant. These issues become more serious in dense and dynamic environments, affecting network performance and scalability.

Future advancements should focus on intelligent optimization techniques, cross-layer design strategies, and incorporation with emerging technologies.

LoRa and LoRaWAN are right candidates to support the evolving demands of IoT systems, offering a practical and efficient solution for widespread, low-power connectivity.

VI. ACKNOWLEDGMENT

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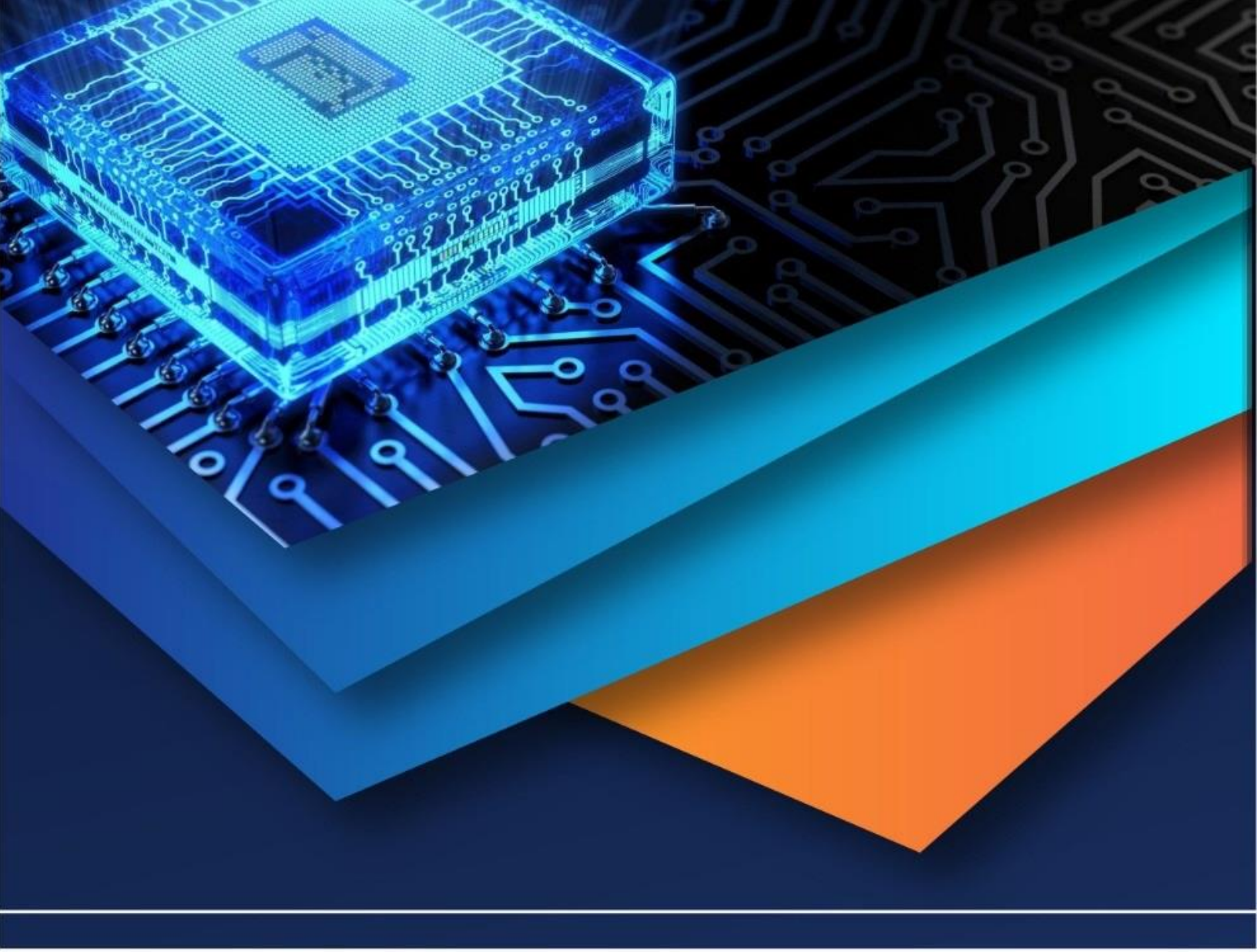

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