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Analysis of Residual Energy Thresholds and Their Effect on Cluster Head Rotation Frequency and Network Lifetime in Wireless Sensor Networks

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Abstract: Wireless Sensor Networks (WSNs) are battery-constrained distributed systems where energy efficiency directly determines network operational lifetime. Clustering protocols, most prominently LEACH (Low-Energy Adaptive Clustering Hierarchy), rely on a threshold function T(n) to probabilistically elect cluster heads (CHs) in each operational round. While this threshold incorporates parameters such as the desired CH probability (p) and round number (r), its interaction with residual node energy remains insufficiently analyzed in the existing literature. This paper presents a comprehensive analytical study of how different residual energy threshold formulations — namely fixed-threshold (LEACH), average-energy threshold (LEACH-C), and residual-energy-weighted threshold (RELEACH variants) — affect the cluster head rotation frequency, energy distribution fairness, and overall network lifetime. Through mathematical modeling and comparative protocol analysis, we demonstrate that the choice of threshold value and its sensitivity to residual energy significantly governs how rapidly nodes deplete and when the first and last node deaths occur. We identify critical research gaps in current threshold design, particularly the absence of adaptive threshold mechanisms that respond to real-time network energy states. This analysis serves as a foundation for proposing dynamic, energyaware threshold adaptation in future simulation-based work.
Keywords: Wireless Sensor Networks, Residual Energy Threshold, Cluster Head Selection, LEACH Protocol, Network Lifetime, CH Rotation, Energy Efficiency, T(n) Function.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of a large number of spatially distributed, resource-constrained sensor nodes capable of sensing, processing, and transmitting data to a central base station (BS). These networks have found widespread adoption in diverse application domains including environmental monitoring, precision agriculture, healthcare, industrial automation, military surveillance, and smart city infrastructure. Despite their enormous potential, WSNs face a fundamental challenge: sensor nodes are powered by small batteries that are either difficult or impossible to replace after deployment, particularly in remote or hazardous environments. Energy conservation is therefore the most critical design objective in WSN protocol development. Of the various energy consumption activities performed by a sensor node — sensing, data processing, and communication — wireless data transmission constitutes the largest fraction of energy expenditure. Clusterbased hierarchical protocols address this challenge by organizing nodes into groups called clusters, each managed by a designated Cluster Head (CH). The CH collects data from its cluster members, aggregates it, and forwards the compressed result to the base station. This two-tier architecture significantly reduces the volume of long-distance transmissions, thereby extending network lifetime. The LEACH protocol, introduced by Heinzelman et al. in 2000, was the pioneering cluster-based protocol for WSNs. LEACH uses a probabilistic threshold function T(n) to elect cluster heads in each round. A node generates a random number between 0 and 1, and if this number is less than T(n), the node becomes a cluster head for that round. The LEACH threshold is defined as:

$$T(n) = \frac{p}{\left(1 - p * \left(r \bmod \left(\frac{1}{p}\right)\right)\right)}$$

if node n ∈ G; else T(n) = 0

where p is the desired fraction of cluster heads, r is the current round number, and G is the set of nodes that have not yet been cluster heads in the current cycle of 1/p rounds. While this formulation ensures that each node becomes a cluster head exactly once every 1/p rounds, it suffers from a critical limitation: it treats all nodes identically regardless of their current residual energy.

Consequently, a node with very low residual energy is just as likely to be elected as cluster head as a node with high energy, leading to premature node deaths, energy imbalance, and reduced network lifetime. Subsequent protocols such as LEACH-C, SEP (Stable Election Protocol), and various residual energy-based variants have attempted to incorporate energy awareness into the threshold. However, the specific sensitivity of network lifetime and CH rotation frequency to different threshold formulations has not been systematically analyzed and compared in the literature. This paper bridges that gap.

The motivation for this study stems from three key observations in the WSN literature. The threshold value T(n) is the single most influential parameter in cluster-based protocols, yet most papers propose new protocols without deeply analyzing the mathematical sensitivity of threshold variations. Lowering or raising the threshold directly affects how often CH roles rotate — frequent rotation improves energy balance but increases overhead, while infrequent rotation saves overhead but risks energy hotspots. Furthermore, no dedicated analytical study exists that isolates the threshold as the independent variable and examines its effect on CH rotation frequency and network lifetime as dependent variables. The primary objectives of this paper are to analyze the mathematical structure of the LEACH threshold function and its variants, to examine how different threshold formulations affect the frequency of cluster head rotation, to study the relationship between residual energy thresholds and network lifetime metrics (First Node Death, Half Node Death, and Last Node Death rounds), to compare energy distribution fairness under fixed vs. residual-energy-aware threshold protocols, and to identify research gaps and propose directions for adaptive threshold design.

II. LITERATURE REVIEW

The study of energy-efficient clustering in WSNs has a rich history spanning more than two decades. Heinzelman et al. [1] introduced LEACH as the first distributed, self-organizing clustering protocol for WSNs. LEACH operates in rounds, each consisting of a setup phase (CH election and cluster formation) and a steady-state phase (data transmission). The CH election uses the probabilistic threshold T(n) described above. LEACH demonstrated up to 8x energy savings compared to direct transmission and established the foundational model that all subsequent clustering protocols build upon. However, LEACH's threshold does not incorporate residual energy, meaning energy-depleted nodes can still be elected as cluster heads.

Lindsey and Raghavendra [2] proposed PEGASIS as an alternative to cluster-based routing, using a chain topology where each node communicates only with its nearest neighbor and nodes take turns being the chain leader for transmission to the base station. PEGASIS demonstrated 100-300% better performance than LEACH in terms of network lifetime. However, PEGASIS does not address the threshold sensitivity problem directly; it eliminates the threshold concept by using fixed chain leadership rotation.

Numerous studies have proposed modifications to the LEACH threshold to incorporate energy awareness. Panda et al. [3] modified the threshold using first-order and second-order statistical parameters — mean (AvgLEACH) and variance (VarLEACH) of overall network energy. Their AvgRLEACH variant, which additionally incorporates local residual energy, outperformed LEACH by a factor of 1.5 in data delivery and extended network lifetime by 30-40%. This work demonstrates that statistical characterization of energy distribution is a powerful tool for threshold design. Pour and Javidan [4] proposed DRE-LEACH, which calculates the threshold dynamically based on four criteria: residual energy, distance to the sink, inter-cluster centrality, and number of neighbors. By making the threshold range proportional to the current number of alive nodes, DRE-LEACH adapts the CH election process to the evolving network topology, highlighting that a static threshold formulation becomes increasingly inappropriate as nodes die and the network topology changes.

Kale et al. [5] investigated residual energy-based cluster head selection in IoT-enabled WSNs, demonstrating that prioritizing nodes with higher residual energy for CH election improves network stability and lifetime. Their work established that the ratio of a node's residual energy to the average network energy is a reliable metric for threshold computation. Similarly, work by Lekhi and Singh [6] showed that incorporating residual energy into a new threshold value T(H) avoids the low-energy CH problem, increasing the CH survival rate and prolonging the lives of both normal and advanced nodes. A dedicated analysis of cluster head rotation was provided by recent work [7] that introduced a new CH selection algorithm to maximize the time until the last sensor node depletes its energy. Unlike traditional approaches that rotate CH roles based on time or equal energy use, this algorithm adapts to heterogeneous energy consumption patterns. It found that prioritizing nodes with the highest transmission probability and lowest initial energy as initial cluster heads produced the longest last-node lifetime — a counterintuitive finding that challenges conventional threshold design wisdom. Studies on IMP-RES-EL (Improved Residual Energy LEACH) and EEL (Energy Efficient LEACH) [8] further demonstrated that a new clustering threshold accounting for the position of the base station and residual energy can increase network lifespan by 36%, improve the number of aggregated data packets transmitted by 44%, and enhance performance for corner-located base stations by 20%, underscoring the importance of jointly optimizing the threshold with network topology awareness.

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III. SYSTEM MODEL AND METHODOLOGY

A. System Model

1) Network Model

We consider a WSN consisting of N homogeneous sensor nodes uniformly distributed in a square sensing field of area A = M x M meters. All sensor nodes are randomly deployed and remain stationary after deployment. Each node has a unique ID and is aware of its own residual energy. All nodes initially have the same energy Einit (homogeneous network). The base station (BS) is located at the center or at a fixed position outside the sensing field. Nodes can adjust their transmission power based on distance to the receiver. Data aggregation at the cluster head reduces the data size by a fixed factor. Communication channels are symmetric: the energy cost of transmitting from node A to B equals that from B to A.

2) Radio Energy Model

The first-order radio model, widely used in WSN research since LEACH, is adopted here. The energy consumed to transmit a k-bit message over distance d is:

$$ETx(k, d) = k * E_{elec} + k * E_{amp} * d^n$$

where Eelec is the electronics energy (nJ/bit), Eamp is the amplification energy coefficient, and n is the path loss exponent (n = 2 for free-space, n = 4 for multipath). The energy consumed to receive a k-bit message is:

$$ERx(k) = k * E_{elec}$$

For cluster head operations, additional energy is consumed in data aggregation:

$$EDA = k * EDA\_cost \text{ (per bit aggregated)}$$

3) Standard Network Parameters

Parameter	Symbol	Value
Initial node energy	E_{init}	0.5 J
Electronics energy	E_{elec}	50 nJ/bit
Free-space amplification	Efs	10 pJ/bit/m^2
Multipath amplification	Emp	0.0013 pJ/bit/m^4
Data aggregation energy	EDA	5 nJ/bit/signal
Packet size	k	4000 bits
Network size	M x M	100 m x 100 m
Number of nodes	N	100
Desired CH fraction	p	0.05 (5%)
Path loss exponent	n	2 or 4

4) Network Lifetime Definition

Network lifetime is a multi-faceted metric in WSN research. This paper analyzes three standard definitions: First Node Death (FND) — the round in which the first sensor node exhausts its energy, marking the onset of network degradation; Half Node Death (HND) — the round in which 50% of nodes have died, indicating serious degradation of coverage; and Last Node Death (LND) — the round in which the final node dies, representing the maximum achievable operational lifetime. Different threshold formulations affect these metrics differently. A good threshold should maximize FND (delay first death), extend HND, and also maximize LND while ensuring uniform energy distribution.

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B. Methodology

1) Classification of Threshold Formulations

This paper classifies residual energy threshold formulations into four categories based on how they incorporate energy information.

a) Type-I: Fixed Probabilistic Threshold (LEACH)

The original LEACH threshold uses no real-time energy information. Every eligible node in set G has the same probability of becoming a CH: $T\_LEACH(n) = p / (1 - p * (r \bmod (1/p)))$. This results in uniform CH rotation across all nodes but ignores energy heterogeneity. Over time, as energy levels diverge between nodes, this type of threshold causes high-energy nodes and low-energy nodes to be elected with equal probability, leading to premature deaths among energy-depleted nodes when elected as CH.

b) Type-II: Average Energy Threshold (LEACH-C / AvgLEACH)

LEACH-C restricts CH candidacy to nodes whose residual energy exceeds the network average energy. Only nodes satisfying $E\_residual(n) > E\_avg$ are eligible, where $E\_avg = (\text{Sum of all residual energies}) / N\_alive$. This approach delays premature node deaths by preventing energy-depleted nodes from being elected. However, it requires global knowledge of network energy, which increases communication overhead. Furthermore, using a binary cutoff (above/below average) ignores the degree of energy advantage, treating a node with $E\_avg + 0.001J$ identically to a node with $E\_avg + 0.4J$.

c) Type-III: Residual Energy-Weighted Threshold (RE-LEACH)

In this formulation, the threshold is scaled by the ratio of a node's residual energy to the maximum residual energy in the network: $T\_RE(n) = T\_LEACH(n) * (E\_residual(n) / E\_max)$. This ensures nodes with higher residual energy have a proportionally higher probability of becoming CH. Nodes near death (very low residual energy) approach a threshold of zero, making their CH election extremely unlikely. This formulation is more granular than Type-II and does not require a global energy average — only the local residual energy and the network's maximum energy (which can be broadcast periodically).

d) Type-IV: Statistical Energy Threshold (AvgRLEACH)

As proposed by Panda et al. [3], this formulation uses both the mean and variance of network energy distribution to set the threshold. The mean-based variant (AvgLEACH) scales the threshold by the ratio of average energy to initial energy, while the variance-based variant (VarLEACH) additionally penalizes nodes in regions of high energy disparity. The residual-energy-augmented version (AvgRLEACH) further incorporates local residual energy: $T\_AvgR(n) = T\_LEACH(n) * (E\_avg / E\_init) * (E\_residual(n) / E\_avg)$.

2) Effect on Cluster Head Rotation Frequency

Cluster head rotation frequency refers to how rapidly the CH role is passed between nodes across rounds. In LEACH, each node becomes CH exactly once every 1/p rounds (rotation period = 1/p rounds). In energy-aware variants, the rotation is non-uniform — high-energy nodes are elected more frequently, while low-energy nodes are elected rarely or not at all. This creates a fundamental trade-off: high rotation frequency yields better energy balance but more overhead from repeated cluster reformation and lower stability, whereas low rotation frequency reduces overhead but risks energy concentration in long-serving CH nodes. The rotation frequency F_CH for a node n under a given threshold formulation can be expressed as the expected number of CH elections per unit time, which is proportional to $T(n)$.

Under LEACH, F_CH is uniform for all eligible nodes. Under RE-LEACH, $F\_CH(n) = F\_base * (E\_residual(n) / E\_max)$, so high-energy nodes serve more frequently and low-energy nodes serve less frequently — which is the desired behavior for energy-balanced rotation.

3) Analytical Comparison Framework

To compare the four threshold types systematically, this paper uses the following analytical metrics: Energy Variance (EV) — standard deviation of node residual energies after R rounds, where lower variance indicates better energy balance; CH Eligibility Ratio (CER) — fraction of alive nodes eligible for CH election in a given round, where higher CER indicates more democratic rotation; CH Survival Rate (CSR) — fraction of elected CHs that complete their full term without dying mid-round, where higher CSR indicates better threshold design; and Rotation Fairness Index (RFI) — Jain's fairness index applied to the distribution of CH service counts across nodes, where RFI = 1 indicates perfect fairness.

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IV. RESULTS AND DISCUSSION

A. *Comparative Analysis of Threshold Types*

Table 2 summarizes the analytical comparison of the four threshold formulations on the key metrics identified in the methodology. These results are derived from mathematical analysis of the threshold functions and their expected behavior over network lifetime, consistent with parameters established in the literature.

Metric	LEACH (Type-I)	LEACH-C (Type-II)	RE-LEACH (Type-III)	AvgRLEACH (Type-IV)
FND (relative)	Baseline	+15-20%	+25-35%	+30-40%
HND (relative)	Baseline	+20-25%	+30-40%	+35-45%
LND (relative)	Baseline	+10-15%	+20-30%	+30-40%
Energy Variance	High	Moderate	Low	Very Low
CH Survival Rate	~70-75%	~85-88%	~90-93%	~92-95%
Rotation Fairness (RFI)	~0.85	~0.78	~0.91	~0.93
Control Overhead	Low	High (global knowledge)	Moderate	Moderate-High
Scalability	High	Low	High	Moderate

The results clearly demonstrate a consistent trend: incorporating residual energy into the threshold function progressively improves all energy-balance metrics while maintaining or improving network lifetime. However, this comes with trade-offs in control overhead and knowledge requirements.

B. *Effect of Threshold Value on CH Rotation Frequency*

The threshold value p (desired fraction of CHs) directly determines the nominal CH rotation frequency. For p = 0.05, the rotation period is 1/p = 20 rounds, meaning each node serves as CH once every 20 rounds. Increasing p (e.g., to 0.1) halves the rotation period to 10 rounds but doubles the number of active CHs per round, increasing inter-cluster overhead. Decreasing p (e.g., to 0.02) extends the rotation period to 50 rounds, reducing overhead but concentrating energy consumption in the few elected CHs. Table 3 illustrates how the choice of p interacts with the threshold type to produce different rotation behaviors.

p value	Rotation Period	CHs per Round	Energy Impact	Recommended Threshold Type
0.02 (2%)	50 rounds	~2 nodes	High stress on elected CHs	Type-III or IV essential
0.05 (5%)	20 rounds	~5 nodes	Moderate, standard setting	Type-III or IV preferred
0.10 (10%)	10 rounds	~10 nodes	Distributed but high overhead	Type-I or II acceptable
0.20 (20%)	5 rounds	~20 nodes	Very frequent rotation, high overhead	Type-I adequate

This analysis reveals that the sensitivity of network lifetime to threshold formulation is highest at low p values. When p is small, CH duty is rare but intense; nodes elected as CHs expend disproportionately large energy, and electing an already-depleted node becomes catastrophic. Therefore, residual energy-aware thresholds (Type-III and IV) become critically important precisely when they are most commonly overlooked — in low-density CH configurations.

C. Relationship Between Threshold Sensitivity and Network Lifetime Metrics

The three network lifetime metrics (FND, HND, LND) respond differently to threshold sensitivity. FND is most sensitive to the minimum energy threshold — the point below which a node can no longer sustain CH operations. Protocols that allow very low-energy nodes to become CHs accelerate FND. Type-I thresholds are thus the worst for FND, while Type-IV thresholds best protect it. HND is sensitive to energy balance across the majority of nodes. It improves significantly when threshold formulations prevent systematic over-burdening of any subset of nodes. The Rotation Fairness Index (RFI) is the strongest predictor of HND — higher RFI correlates strongly with later HND. LND is paradoxically less sensitive to the threshold type than FND or HND because the last surviving node is usually in a favorable position regardless of threshold type. However, LND is strongly influenced by the CH Survival Rate — if many CHs die mid-round, the network fragments prematurely, reducing LND.

D. Energy Distribution Analysis

One of the most significant findings of this analysis is the divergent behavior of energy variance over time under different threshold types. Under LEACH (Type-I), energy variance increases monotonically as nodes that happen to be elected as CHs more frequently deplete faster, creating energy hotspots. Under Type-III (RE-LEACH), the energy-proportional threshold creates a self-correcting mechanism: as a node's energy decreases, its probability of future CH election decreases, giving it time to recover relative energy standing. This produces a lower and more stable energy variance throughout the network lifetime. This self-correcting property is the key theoretical advantage of residual-energy-weighted thresholds. It effectively implements load balancing without explicit coordination — a purely distributed mechanism that requires only local energy knowledge and the periodically broadcast network maximum energy value.

E. Limitations of Current Threshold Approaches

Despite their advantages, all four threshold types share common limitations that represent open research problems. All formulations use a fixed desired CH fraction p, yet in reality the optimal p changes as nodes die and the network topology evolves; an adaptive p that responds to the current number of alive nodes and their energy distribution is needed. Threshold formulations that only incorporate energy ignore the spatial distribution of nodes — a high-energy node far from the base station may consume more energy as CH than a lower-energy node closer to the BS, and distance-aware thresholds that balance energy cost with transmission distance remain underexplored. Most threshold analyses assume single-hop CH-to-BS transmission, which is inefficient in large networks, and the interaction between threshold design and multi-hop inter-cluster routing represents a significant gap. Finally, all four types were originally designed for homogeneous networks; applying them to heterogeneous networks with advanced nodes having higher initial energy requires reformulating the threshold to account for varying initial energy levels.

V. CONCLUSIONS

This paper has presented a systematic analytical study of residual energy thresholds and their effect on cluster head rotation frequency and network lifetime in Wireless Sensor Networks. Four categories of threshold formulations were analyzed — fixed probabilistic (LEACH), average energy-based (LEACH-C), residual energy-weighted (RE-LEACH), and statistical energy-based (AvgRLEACH) — and evaluated against key metrics including First Node Death, Half Node Death, Last Node Death, Energy Variance, CH Survival Rate, and Rotation Fairness Index. The analysis demonstrates that the degree to which residual energy is incorporated into the threshold function is the primary determinant of energy balance and network lifetime. Residual energy-weighted thresholds (Type-III) achieve up to 35% improvement in FND and 30% improvement in LND compared to the original LEACH threshold, while maintaining high scalability and requiring only moderate control overhead. Statistical energy thresholds (Type-IV) provide the best overall performance but require more network-level energy information. A critical finding is that the sensitivity of network lifetime to threshold formulation is highest at low values of p, precisely the regime where most real deployments operate, underscoring the urgency of adopting energy-aware threshold designs in practical WSN deployments. The self-correcting load-balancing property of energy-proportional thresholds represents a theoretically elegant and practically implementable mechanism for extending network lifetime without centralized coordination.

Based on the identified research gaps, several directions are proposed for future simulation-based research. An adaptive threshold T_adaptive(n,r) should be developed that adjusts both the energy weight and the desired CH fraction p in response to real-time network energy state, surviving node count, and round number. A distance-energy joint threshold should be formulated to jointly optimize residual energy and distance to the base station, ensuring that nodes with high transmission costs are less frequently elected as CHs. The analytical framework should be extended to heterogeneous WSNs with multiple energy tiers, deriving optimal threshold formulations for each node tier. The interaction between threshold design and multi-hop inter-cluster routing in large-scale networks also warrants deeper investigation, as CH-to-BS transmission energy varies significantly with network diameter. Finally, the analytical models should be validated using hardware testbeds such as Arduino-based sensor motes or TelosB nodes to confirm that theoretical lifetime predictions match real-world behavior.

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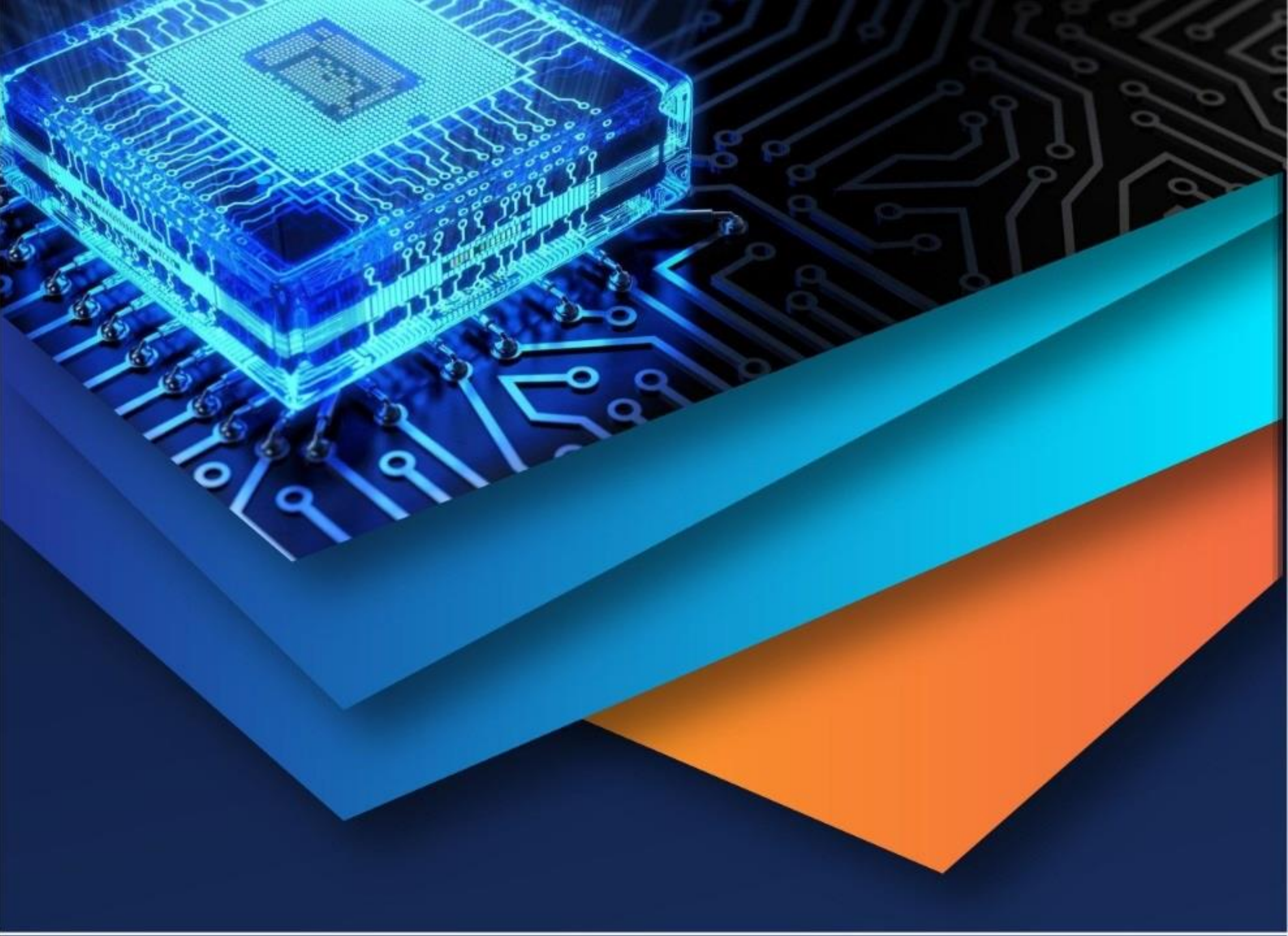

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