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Energy Harvesting Techniques Enabling Self-Powered IoT Devices

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Abstract: The swift expansion of the Internet of Things (IoT) has heightened the difficulty of supplying power to billions of distributed, low-energy devices. Traditional batteries impose restrictions on longevity, scalability, and sustainability. Energy harvesting (EH) facilitates self-powered or energy-autonomous IoT nodes by transforming ambient energy—mechanical, solar, wind, thermal, radio-frequency (RF), and sound—into electrical energy. This concise review outlines the fundamental EH mechanisms, architectures, transducers, power management techniques, storage solutions, and security issues pertinent to IoT. The focus is on practical trade-offs, market readiness, and prospective research avenues aimed at achieving sustainable and secure IoT and Internet of Nano-Things (IoNT) systems.
Keywords: energy harvesting; IoT; batteries; piezoelectric; photovoltaic; solar energy; wind energy; thermal energy.

I. INTRODUCTION

The Internet of Things (IoT) connects sensors, actuators, and embedded processors throughout smart cities, healthcare, industry, transportation, aerospace, and environmental monitoring. The primary limitation is the power supply, which is constrained by battery lifespan, maintenance expenses, and environmental effects. Energy harvesting presents a sustainable solution by prolonging battery life or facilitating operation without batteries. This review encapsulates the fundamental concepts and technologies that support self-powered IoT.

II. ENERGY HARVESTING ARCHITECTURES

Two primary architectures are employed:

1) Harvest–Store–Use: The energy that is harvested is processed and stored in batteries or supercapacitors prior to supplying power to the load. This method accommodates intermittent energy sources but results in conversion losses and degradation of storage.
2) Harvest–Use: Energy is utilized to directly power the load without the need for long-term storage, thereby minimizing losses and costs. This method is ideal for ultra-low-power, duty-cycled IoT nodes. Essential design considerations encompass impedance matching, voltage regulation, and maximum power point tracking (MPPT).

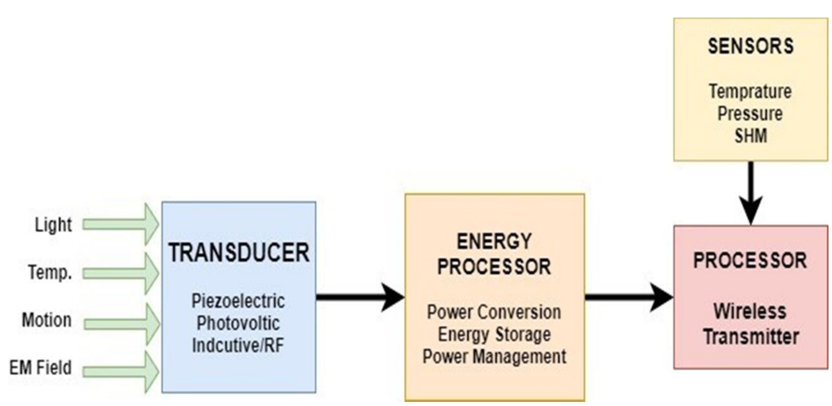

Figure1.Aworkflowofenergyharvesting

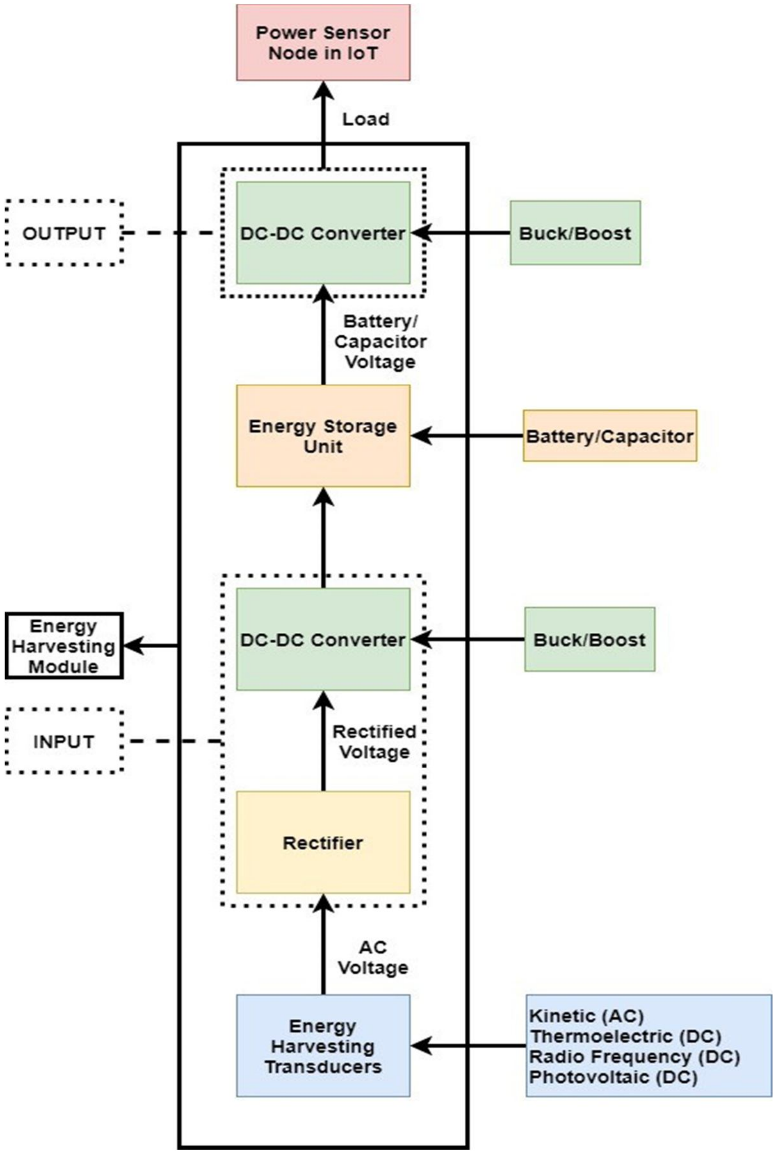

Figure2.Mechanismforvariousenergyharvestingtechniques

III. ENERGY HARVESTING MECHANISMS

A. Mechanical and Vibration Energy

Mechanical energy harvesting (EH) utilizes vibration, strain, and motion through the use of piezoelectric, triboelectric, electromagnetic, or electrostatic transducers. Among these, piezoelectric energy harvesting (PEH) stands out as the most developed technology, attributed to its high conversion efficiency and straightforward structure. Its applications span across various fields, including industrial machinery, roadways, human motion, and aerospace structures. Furthermore, aeroelastic phenomena such as flutter, galloping, and vortex-induced vibrations present significant potential for wind-driven and aerospace Internet of Things (IoT) systems.

B. Solar Energy

Photovoltaic (PV) energy harvesting is the most commonly utilized energy harvesting technique, owing to its high-power density and the maturity of the technology. Crystalline silicon is primarily used in outdoor applications, while amorphous silicon is favoured for indoor applications. Solar energy harvesting is frequently integrated with Maximum Power Point Tracking (MPPT) and hybrid storage solutions for wireless sensor networks (WSNs).

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C. Wind, Sound, RF, and Thermal Energy

Wind Energy Harvesting (EH) employs turbines or flow-induced vibrations for outdoor Internet of Things (IoT) applications. Acoustic Energy Harvesting converts surrounding noise into electrical energy, albeit with limited power output. Radio Frequency (RF) Energy Harvesting facilitates concurrent wireless power and data transmission, although the amount of harvested power is minimal and varies with distance. Thermal Energy Harvesting encompasses thermoelectric generators that utilize temperature gradients and pyroelectric devices that harness temperature fluctuations, making them appropriate for waste-heat recovery and wearable technologies.

Reference	Source	PowerDensity
[103]	Mechanical/Piezoelectric	[0.11–7.31]mWg^2/cm^3
[7,104]	Radiofrequency	1.2×10^{-5}–15mW/cm^2
[105]	Solar	[0.006–15]mW/cm^2
[105]	Thermoelectrical	[15–60]µW/cm^3
[106,107]	Wind	[0.065–28.5]mW/cm^2

Table1. Power density of various sources

IV. TRANSDUCERS AND ENERGY SENSING

Energy transducers convert ambient energy into electricity, including piezoelectric generators, PV cells, rectennas, thermoelectric, and pyroelectric devices. Energy-positive sensing occurs when harvested energy exceeds signal acquisition power, enabling autonomous operation. Efficient transducer selection, bandwidth matching, and electrical interface design are critical.

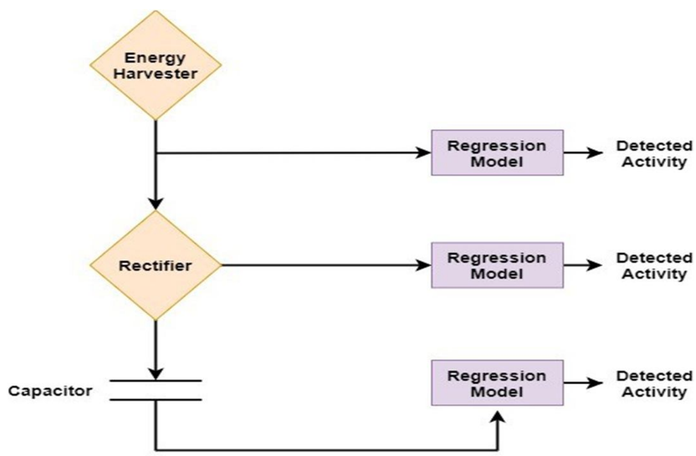

Figure3.Typesofsignalsfromenergyharvesting

Reference	Given Source (S.)	Mechanism	Source Power	Harvested Power
[33]	Lab	MechanicalVibration	10m/s^2(at1KHz)/0.8m(at1Hz)	80µW/cm^2
[113]	Human	Motion/Vibration	1m/s^2(at50Hz)/0.5m(at1Hz)	4µW/cm^2
[113]	Industrial	Motion/Vibration	10m/s^2(at1kHz)/1m(at5Hz)	100µW/cm^2
[113]	Human	ThermalEnergy	20mW/cm^2	30µW/cm^2
[113]	Industrial	ThermalEnergy	100mW/cm^2	1–10mW/cm^2
[113]	Indoor	AmbientLight	0.1mW/cm^2	10µW/cm^2
[113]	Outdoor	AmbientLight	100mW/cm^2	10mW/cm^2
[113]	GSMBaseStation	RadioFrequency	0.3µW/cm^2	0.1µW/cm^2

Table2. Energy sources for IoT applications

V. POWER MANAGEMENT AND ENERGY STORAGE

Efficient power management balances harvested energy and consumption through duty cycling, adaptive operation, and low-power modes. Accurate power profiling is essential for reliable operation.

A. *Energy Storage*

- Batteries provide high energy density but suffer from limited lifetime and maintenance issues.
- Supercapacitors offer long cycle life and fast charge/discharge but lower energy density and self-discharge.

Hybrid battery–supercapacitor solutions are commonly used to balance energy and power demands.

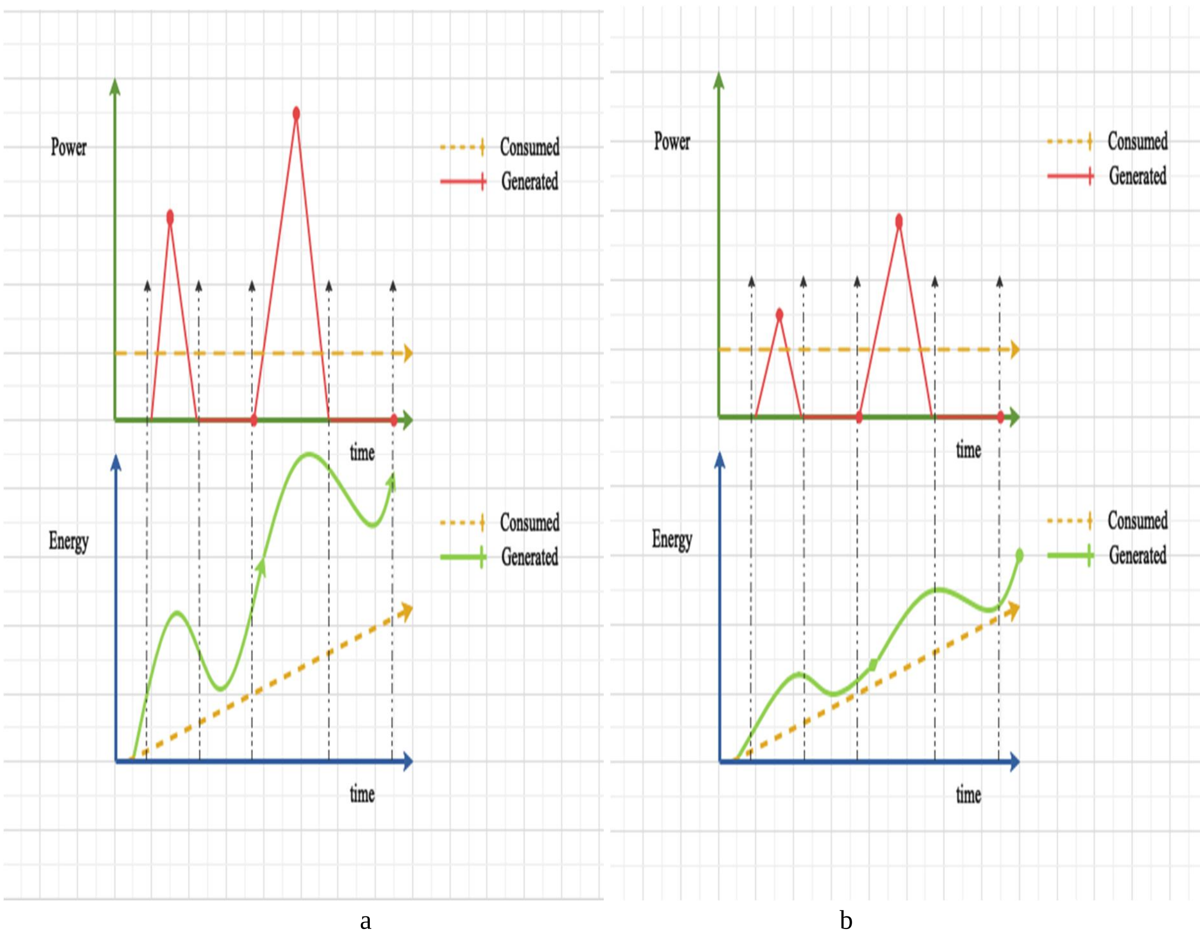

Figure4. PowerManagement:(**a**)Continuousoperationmode.(**b**)Discontinuousoperationmode.

VI. POWER MANAGEMENT INTEGRATED CIRCUITS (PMICS)

PMICs integrate rectification, MPPT, regulation, protection, and storage control, enabling practical EH-based IoT systems. Commercial solutions from E-peas, Texas Instruments, Cypress, Maxim, and STMicroelectronics support solar, thermal, and vibration sources with ultra-low quiescent current, targeting wearable devices and WSNs.

VII. SECURITY CHALLENGES AND ENERGY TRADE-OFFS

Energy harvesting IoT networks are vulnerable to eavesdropping, denial-of-service (energy depletion and jamming), spoofing, side-channel attacks, and device tampering. Limited harvested energy restricts conventional cryptographic solutions, creating a trade-off between security and energy efficiency. Energy-aware security protocols and physical-layer security are promising mitigation strategies.

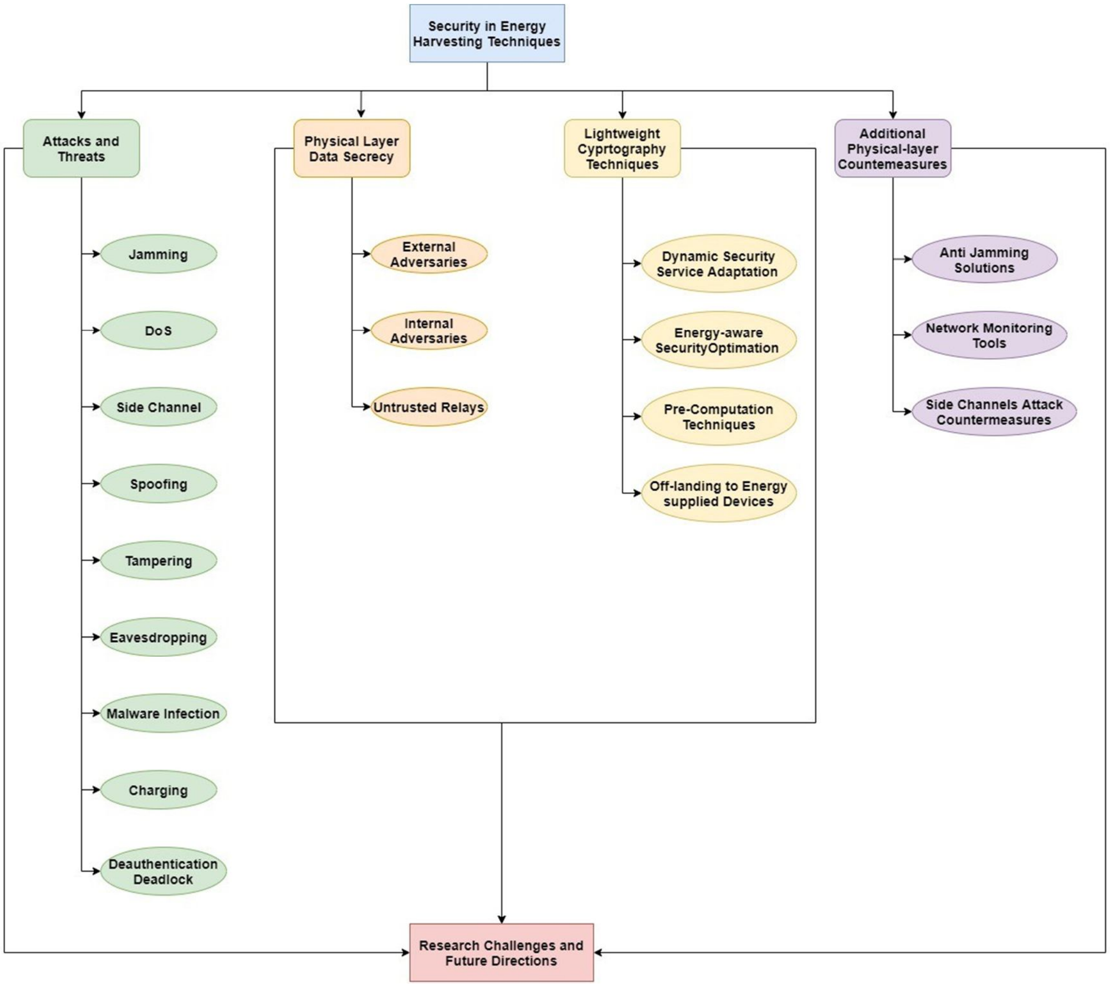

Figure5. Security in energy harvesting techniques.

VIII. APPLICATIONS AND COMMERCIAL SOLUTIONS

Existing EH-powered products demonstrate feasibility across domains: solar-powered wireless tags for smart cities, vibration-powered industrial sensors, RF-powered RFID systems, and hybrid multi-source harvesters. Key applications include agriculture, infrastructure monitoring, healthcare, aerospace, and wearable electronics.

IX. CONCLUSIONS AND FUTURE DIRECTIONS

Energy harvesting is a key enabler for sustainable and maintenance-free IoT. Despite challenges such as intermittency, low power density, storage aging, and security risks, advances in materials, transducers, PMICs, and system-level optimization continue to improve viability. Future research will emphasize nanoscale harvesting, highly integrated EH–PMIC–storage platforms, and secure energy-aware protocols, supporting the evolution toward the Internet of Nano-Things (IoNT).

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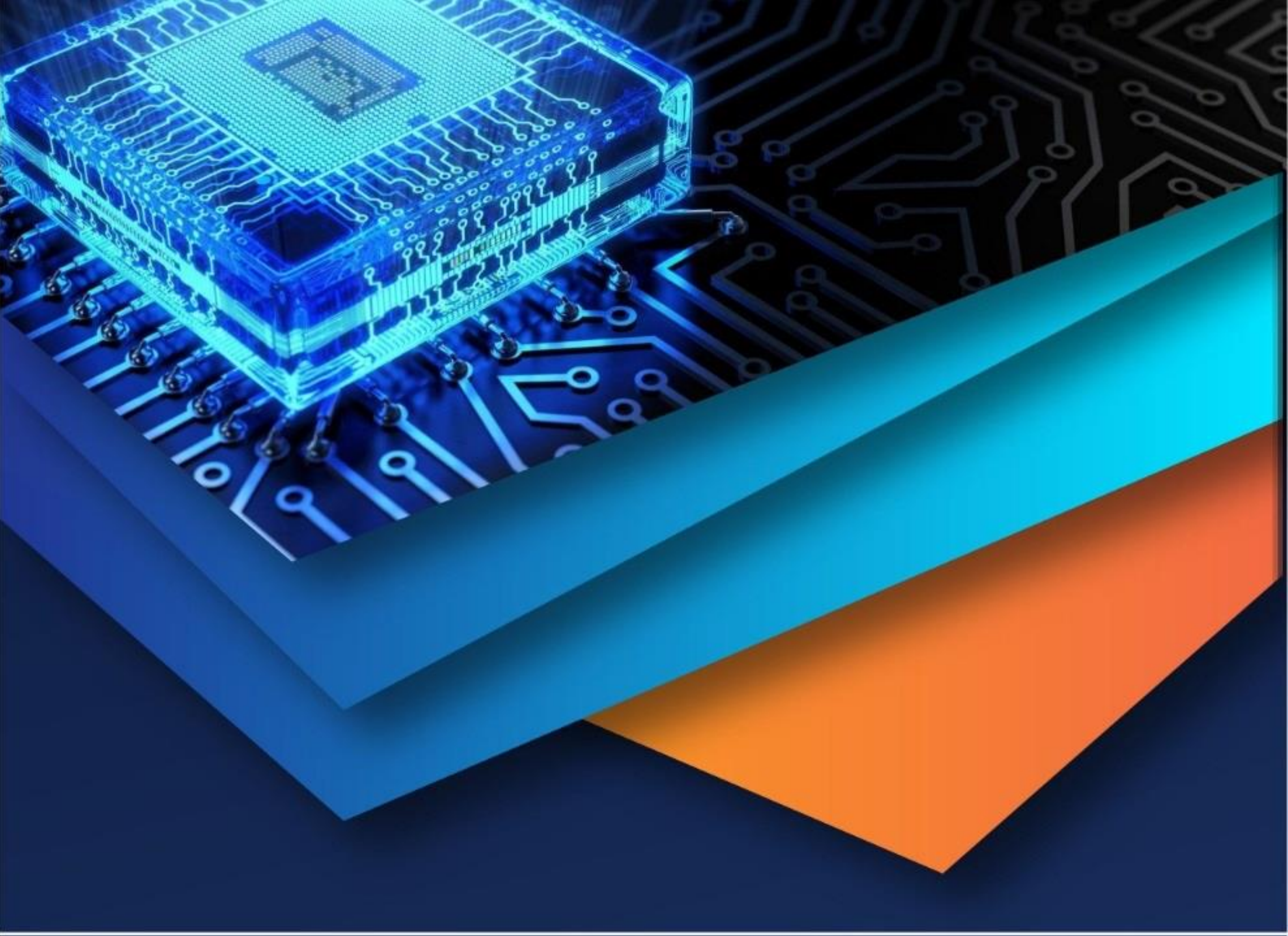

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