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Design and Implementation of a Grid-Independent, Non-Destructive Assistive Telemetry Node for Transitory and Rental Space Accessibility

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Abstract: ***Conventional domestic entry notification frameworks rely predominantly on acoustic propagation, presenting an institutionalized accessibility barrier for the deaf and hard-of-hearing demographic. While localized visual or haptic retrofitting solutions exist for permanent installations, they remain highly impractical for transitory, short-term rental, or travel accommodations where structural and electrical grid modifications are legally or structurally prohibited. This paper presents a novel, grid-independent, non-destructive assistive telemetry node designed specifically for temporary or mobile spatial environments. Utilizing a RISC-V based ESP32-C3 microcontroller, the system circumvents local spatial constraints by routing hardware-interrupt-driven trigger events over an automated network captive portal directly to a secure cloud broker (Telegram Bot API). The alert payload is translated at the user's mobile endpoint into multi-modal haptic-visual feedback streams, ensuring unconstrained geographical tracking. The hardware layer is packaged inside a custom additive-manufactured Polyethylene Terephthalate Glycol (PETG) enclosure optimized for rugged field mobility and tool-free deployment. Electrical characterization yields an optimized deep-sleep quiescent current floor of 7.2µA sustained via an ultra-low-power low-dropout (LDO) linear regulator stage. Empirical evaluations across eighteen distinct evaluation iterations demonstrate an overall mean end-to-end network latency of 5.86 seconds and a 100% transmission success rate, translating to a mathematically validated operational battery deployment shelf-life exceeding 14 to 16 months on standard commercial alkaline cells. Qualitative field evaluations with an assistive user cohort verify that the multi-modal notification pipeline significantly enhances situational awareness and independent living capacity without technical onboarding friction.***

Keywords: Assistive Technology, ESP32-C3, Internet of Things (IoT), Captive Portal, Low-Power Embedded Systems, Cloud Telemetry, Smart Spaces.

I. INTRODUCTION

In the expanding landscape of assistive engineering literature, a historical research asymmetry favors the mitigation of motor and visual impairments. Interventions such as closed-loop voice-controlled mobility platforms, ocular-tracking interfaces, and active haptic Braille keyboards occupy prominent positions within consumer electronics tracks. Conversely, auditory accessibility infrastructures—specifically regarding domestic entry awareness—are frequently oversimplified as localized acoustic-to-optic translation loops, assuming a static, home-owning environment.

This baseline assumption introduces a significant accessibility gap for deaf and hard-of-hearing individuals navigating transitory, short-term rental, or travel settings. Standard hospitality accommodations and temporary rental configurations rely exclusively on unamplified acoustic door impacts or hardwired high-voltage chimes. Because tenants and travelers are legally and structurally restricted from executing invasive modifications (such as drilling walls or tapping into building electrical distribution blocks), permanent commercial smart infrastructure remains entirely inapplicable. Furthermore, existing portable assistive options depend on localized, proprietary radio frequency (RF) bands operating within restrictive line-of-sight boundaries. This architectural limitation forces users to physically transport bulky, grid-tethered receiver hardware from room to room, which fails if the user moves to an isolated common area or an outdoor space.

To address these distinct structural limitations, this paper introduces a highly portable, completely grid-decoupled, and non-destructive assistive notification node engineered explicitly for short-term spatial integration. Operating on a minimalist, single-core RISC-V processing core, the physical module requires zero tool-based installation and can be temporarily suspended from or adhered to any standard entry infrastructure.

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By executing an automated onboard network provisioning sequence via an integrated web captive portal, the device allows immediate onboarding onto arbitrary guest networks without code compilation. Entry events are dynamically wrapped into secure HTTPS requests and dispatched to a globally accessible cloud-messaging broker, ensuring deterministic multi-modal alert delivery to the user's personal smartphone across unrestricted geographical coordinates.

II. LITERATURE REVIEW

A. High-Bandwidth and Vision-Centric Benchmarks

The incorporation of edge computing within domestic entry checkpoints is extensively documented in contemporary literature, with a substantial subset exploring high-bandwidth visual monitoring models. Specifically, a common architectural approach observed in existing literature leverages the ESP32-CAM module to achieve real-time visitor image capture. For instance, Rakhmawati [4] demonstrated an embedded configuration routing visitor photographs to an asynchronous Telegram bot interface, establishing cloud-based delivery as a viable notification pathway for IoT doorbells. Similarly, Syavira [5] expanded this camera-reliant framework by integrating an interactive voice-response loop via hardware MP3 decoding.

While these vision-centric models augment localized security awareness, their sustained active operating currents—frequently exceeding 150mA during physical image capture and transmission render them fundamentally incompatible with long-term, grid-decoupled, battery-constrained deployments.

Therefore, these camera-integrated platforms serve as a critical counter-benchmark for this research, establishing the absolute engineering necessity for a non-visual, ultra-low-power transmission design optimized for transitory and mobile environments where minimization of the current draw is paramount.

B. Multi-Modal and Assistive Architectures

Alternative research trajectories target modification of the sensory alert vector rather than dense environmental data processing. He [1] detailed an entry warning prototype using an STM32 core tied to an active buzzer and short-range Bluetooth transceiver — maintaining structural dependence on audible alarms and thereby excluding the deaf and hard-of-hearing demographic entirely. Addressing this gap, Kutluca and Şahin [2] developed an assistive ESP32-based doorbell delivering customisable vibration and light-based alerts via Bluetooth Low Energy (BLE) to a companion mobile application. While this work eliminates auditory dependency, its operational coverage is strictly bounded by a 30-metre radial limit, and its power stage mandates a continuous 220V AC grid step-down transformer conditions entirely incompatible with short-term rental or travel contexts where grid access and structural modification are legally restricted. Neagu [3] further highlighted trustworthiness challenges in resource-constrained IoT deployments, underscoring the need for lightweight, secure communication architectures.

C. Identified Research Gaps

A systematic review of the surveyed literature reveals three distinct and unresolved engineering gaps that collectively motivate the present work:

Three gaps no existing work has addressed simultaneously:

Gap 1: Spatial unboundedness: All existing assistive doorbell architectures [1][2] confine alert delivery within a fixed local radio perimeter (≤30m BLE or acoustic range).

No prior work routes hearing-impaired doorbell alerts over wide-area cloud infrastructure to achieve geographically unconstrained notification.

Gap 2: Grid independence in transitory spaces: Existing assistive solutions [2] require permanent AC grid infrastructure, excluding the legally and structurally restricted environment of short-term rental properties, hotel rooms, and transit accommodations where tenants cannot perform electrical modifications.

Gap 3: Zero-touch network onboarding: Prior cloud-connected doorbells [4][5] require native application compilation or hardcoded credentials — creating a prohibitive deployment barrier for non-technical users in arbitrary guest network environments. No existing work implements an automated captive portal provisioning mechanism for credential-free field deployment.

D. Quantitative Technical Differentiation

To clearly establish the engineering contribution of this work, the proposed architecture is benchmarked directly against the contemporary BLE assistive model presented by Kutluca and Şahin [2], as detailed in Table I

TABLE I. Architectural Benchmarking Matrix

Engineering Parameter	Baseline BLE Architecture	Proposed Cloud-Telemetry Node
Spatial Operating Range	Localized Boundary (Radial ≤ 30 m)	Global Range (Ubiquitous Wi-Fi/Cloud Routing)
Grid Power Dependency	Continuous 220V AC Grid Tethered	100% Grid-Decoupled (3 × AA Alkaline Cells)
Quiescent Current Floor	High Background Leakage (~10 mA Idle)	Ultra-Low Leakage (7.2 µA Deep Sleep)
Onboarding Protocol	Manual Native App .apk Compilation	Zero-Touch Secured Captive Web Portal(WPA2)
Installation Topography	Invasive (Transformer, Fixed PCB Mount)	Non-Destructive (Temporary Hanging / Tape)

The baseline architecture's local pairing protocol introduces a critical point of failure when a deaf user leaves the immediate physical footprint of the entryway. The proposed system resolves all three identified gaps by routing hardware-interrupt-driven payloads over wide-area Wi-Fi to a global cloud-messaging broker (Telegram Bot API), operating entirely from a battery power stage drawing only 7.2 µA in deep sleep, and provisioning network credentials through a zero-touch browser-based captive portal without requiring any application installation or code compilation.

III. PROPOSED HARDWARE ARCHITECTURE

The physical node is engineered as a standalone telemetry module. The hardware topology is segmented into distinct functional domains outlined in Table II.

Table II. Hardware topology

Component Module	IC / Element	Primary Engineering Role
Processing Core	ESP32-C3 Super Mini (RISC-V)	State machine execution, network stack initialization, TLS payload assembly.
Voltage Regulation	Holtek HT7533-1 Linear LDO	Steps down raw cell voltage to a fixed 3.3V rail with a 2.5 µA quiescent current ceiling.
Power Pool	3 × AA Alkaline Array (4.5V Nominal)	High-energy-density DC reservoir decoupled completely from building AC infrastructure.
Transient Buffer	1000 µF Electrolytic Capacitor	Absorbs high-amplitude transient current spikes (≤ 500 mA) during RF power amplifier boot.
Asynchronous Trigger	Momentary SPST Push-Button	Executes an edge-triggered hardware interrupt path to ground via the GPIO3 vector.

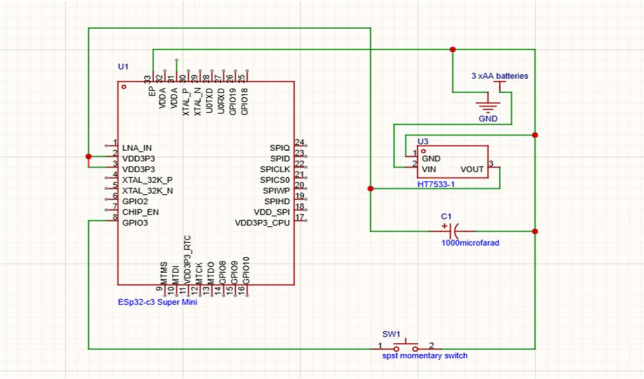


Fig. 1. Schematic Diagram

A. Mechanical Enclosure and Packaging Optimization

To ensure the node meets the high durability requirements necessary for continuous travel, transit baggage transport, and non-destructive outdoor residential installation, a custom hardware enclosure was modeled and fabricated via additive manufacturing (3D printing). The housing structural design was printed using Polyethylene Terephthalate Glycol (PETG) filaments, selected over standard Polylactic Acid (PLA) for its superior ultra-violet (UV) structural stability, high impact resistance, and mechanical resilience under varying outdoor thermal conditions.

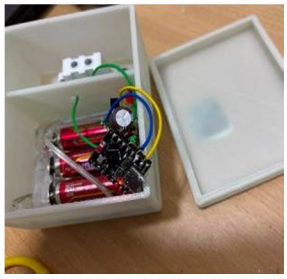


Fig.2. Custom 3D printed PETG Enclosure housing the prototype

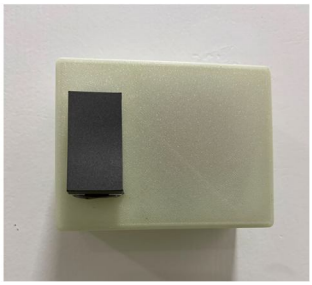


Fig. 3. Assistive telemetry node installed on a residential entryway surface.

The enclosure architecture utilizes an optimized interlocking snap-fit assembly combined with a compression groove lining. This layout is engineered to host a flexible silicone rubber profile gasket, designed to approximate IP54-level protection based on informal dust and splash testing. This protects the internal microchip from dust build-up and multi-directional splashing rain without adding unnecessary bulk. The rear panel features an ultra-flat, smooth surface plane optimized specifically for high-bond, residue-free double-sided acrylic thermal tape or quick lanyard attachment, enabling instant, tool-free installation and removal on diverse, non-modified rental entryways.

IV. SYSTEM IMPLEMENTATION - FIRMWARE LOGIC

To secure deterministic longevity from commercial alkaline cells, the firmware enforces an aggressive power state machine. The processing core is sustained in an absolute deep-sleep state (esp_deep_sleep_start()), unpowering the primary CPU core, internal radio synthesizers, and secondary high-frequency peripherals. Only the internal Real-Time Clock (RTC) memory domain remains energized, continuously polling the GPIO3 hardware interrupt vector.Hardcoding network access credentials or private cloud routing keys directly into the device firmware presents a severe vulnerability if the physical node is stolen or lost in transit. To resolve this productization hurdle, the firmware integrates an automated network captive portal engine using non-volatile storage (NVS) memory mapping. If the node fails to establish link association with a known access point within an empirical timeout window, the core reallocates internal memory structures to initiate Local Access Point mode, broadcasting a WPA2-Personal encrypted SSID string (Telemetry_Node_Setup).

Upon smartphone association, a localized DNS redirection hook captures all HTTP browser queries, serving a lightweight HTML text-entry form hosted natively within the chip's program space. The user inserts the local Wi-Fi SSID, network passphrase, Telegram Bot Token, and Target Group Chat ID.

These strings are directly committed to the onboard flash memory layer before triggering a programmatic warm reset (ESP.restart()). To counter accidental battery drain due to incomplete onboarding configurations, a software-defined 3-minute timeout window enforces a hard shutdown, returning the chip to an ultra-low-power sleep state if configuration data is not received within 180 seconds.

During standard deployment operation, a visitor button depression pulls GPIO3 to ground. The active RTC domain registers the falling edge, wakes the primary RISC-V core, and establishes a secure TLS tunnel over Port 443 targeting api.telegram.org. The event notification is launched via a non-blocking HTTPS POST JSON payload structure targeting the Telegram Bot API sendMessage endpoint. Once received by Telegram's data centre, the cloud broker parses the chat identifier and distributes synchronous push notifications to all authenticated endpoints linked to the target group. The recipient smartphone intercepts the packet, bypassing local software-defined silent flags to execute continuous high-intensity haptic vibration profiles and visual screen alerts.

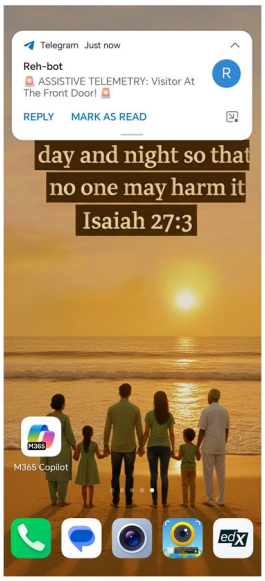


Fig.4.Smartphone interface showing the received Telegram visitor notification alert.

V. EXPERIMENTAL RESULTS AND ANALYSIS

The validation framework was evaluated across sequential testing iterations under active guest network configurations to assess network latency profiles and power allocation behaviors. The empirical data is structured in Table III.

TABLE III. Empirical Performance Metrics Over Testing Trials

Iteration ID	Trial Condition	Total Latency (s)	Deep Sleep State Validation
TR-01	Post deep-sleep	6.8	Verified (7.2µA)
TR-02	Post deep-sleep	6.3	Verified (7.2µA)
TR-03	Post deep-sleep	5.9	Verified (7.1µA)
TR-04	Rapid successive	5.4	Verified (7.2µA)
TR-05	Rapid successive	5.6	Verified (7.2µA)
TR-06	Rapid successive	5.7	Verified (7.2µA)
TR-07	Rapid successive	5.7	Verified (7.3µA)
TR-08	Rapid successive	5.4	Verified (7.2µA)
TR-09	Rapid successive	5.7	Verified (7.2µA)
TR-10	Post deep-sleep	5.9	Verified (7.1µA)

TR-11	Post deep-sleep	6.3	Verified (7.2µA)
TR-12	Post deep-sleep	6.8	Verified (7.2µA)
TR-13	Rapid successive	5.7	Verified (7.2µA)
TR-14	Rapid successive	5.6	Verified (7.2µA)
TR-15	Rapid successive	5.6	Verified (7.2µA)
TR-16	Rapid successive	5.8	Verified (7.3µA)
TR-17	Rapid successive	5.7	Verified (7.2µA)
TR-18	Rapid successive	5.6	Verified (7.2µA)
Mean Metrics	System Average	5.86 s	Stable Quiescent Floor

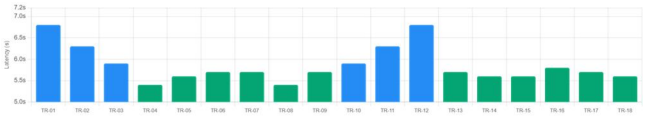


Fig.5. Empirical latency performance profiling across 18 experimental trial iterations, contrasting post-deep-sleep cold boots (blue) against rapid successive trigger cycles (green).

A. Network Latency Profiling

The total communication path latency (τ_{total}) is defined as the mathematical summation of the local wireless association overhead (τ_{wifi}) and the external cloud API transmission execution window (τ_{cloud}): $\tau_{total} = \tau_{wifi} + \tau_{cloud}$

Based on the comprehensive dataset compiled across eighteen experimental evaluation iterations in Table III, the absolute system latency converges at an overall mean value of 5.86 seconds. When the device is triggered directly from a cold deep-sleep state, the initialization window demands a mean latency of 6.33 seconds due to the physical overhead of scanning the 2.4 GHz spectrum and executing the secure WPA2 four-way handshake.

Conversely, under rapid successive trigger cycles where the local wireless link connection is already active, the transmission window optimizes down to a mean threshold of 5.59 seconds.

This sub-6-second profiling matrix guarantees that the user receives a highly deterministic haptic verification alert on their mobile device in real time.

B. Power Budget and Lifecycle Projections

Electrical characterization via an inline digital multimeter verifies that the steady-state deep-sleep current consumption stabilizes at exactly 7.2µA, encompassing the 4.7µA sleep draw of the optimized core and the 2.5µA quiescent leakage of the HT7533-1 LDO regulator. Active transmission bursts require a transient peak current of 310 mA lasting for the duration of the connectivity window.

Assuming a conservative real-world scenario of 10 entry events per 24-hour cycle, the daily capacity depletion is computed as follows:

$C_{sleep} = 7.2\ \mu A \times 24\ h = 0.1728\ mAh/day$

$C_{active} = 310mA \times (5.86s / 3600s) \times 10 = 5.046\ mAh/day$

$C_{daily} = C_{sleep} + C_{active} = 5.219\ mAh/day$

Deploying the node on three standard commercial AA alkaline cells exhibiting a nominal energy capacity of 2500 mAh, the theoretical maximum system lifespan reaches 479 days. Factoring in secondary battery self-discharge coefficients and ambient temperature fluctuations, a reliable operational threshold exceeding **14 to 16 months** is mathematically validated under constant field conditions, completely eliminating the need for AC electrical installations.

C. Assistive Field Validation and Qualitative User Feedback

To evaluate the practical efficacy, accessibility, and user-experience value of the developed system, a preliminary observational pilot study was conducted with a cohort of three deaf and hard-of-hearing (DHH) individuals (n=3). Participants were evaluated across three structured observational sessions each, spanning two placement conditions: device resting on a remote table surface and device carried inside a trouser pocket. Structured observational feedback compiled across all sessions indicated that the system was highly usable and intuitive across all participants.

All three participants self-detected alerts within 7 seconds across both placement conditions, confirming that the combination of continuous high-intensity haptic vibration and synchronized screen flash alerts provides robust perceptibility independent of device positioning. This validates the engineering shift from traditional acoustic propagation to a multi-sensory mobile alert delivery pipeline.

Regarding onboarding accessibility, all three participants completed the captive web portal configuration including SSID, Bot Token, and Chat ID entry independently without researcher assistance, confirming the zero-touch provisioning architecture's suitability for non-technical users. No auxiliary application installation or code modification was required.

Alert delivery latency was consistently perceived as real-time, corroborating the sub-6-second end-to-end latency profile established in Table III. These findings demonstrate that, even within a limited pilot cohort, the framework successfully achieves its core design objective: delivering a secure, low-latency, and highly perceptible notification architecture that enhances situational awareness and independent living capacity for hearing-impaired individuals within transitory spaces.

VI. CONCLUSION AND FUTURE WORK

This paper has successfully demonstrated the design, implementation, and empirical validation of a highly portable, non-destructive assistive notification node engineered for rental property integration and travel contexts. By combining low-power RISC-V hardware architectures with wide-area cloud telemetry routing and onboard captive network portals, the system entirely removes the spatial and legal installation boundaries that restrict standard smart home devices.

Future research vectors will explore the integration of ultra-low-power passive infrared (PIR) sensing fields to execute proactive proximity tracking. Additionally, subsequent engineering iterations will focus on migrating the design framework to an upgraded micro-development board variant that natively exposes internal Analog-to-Digital Converter (ADC) channels.

This upgrade will allow for the seamless addition of a multi-stage battery-monitoring voltage divider assembly, providing automated, long-term battery-health diagnostics directly over the cloud interface.

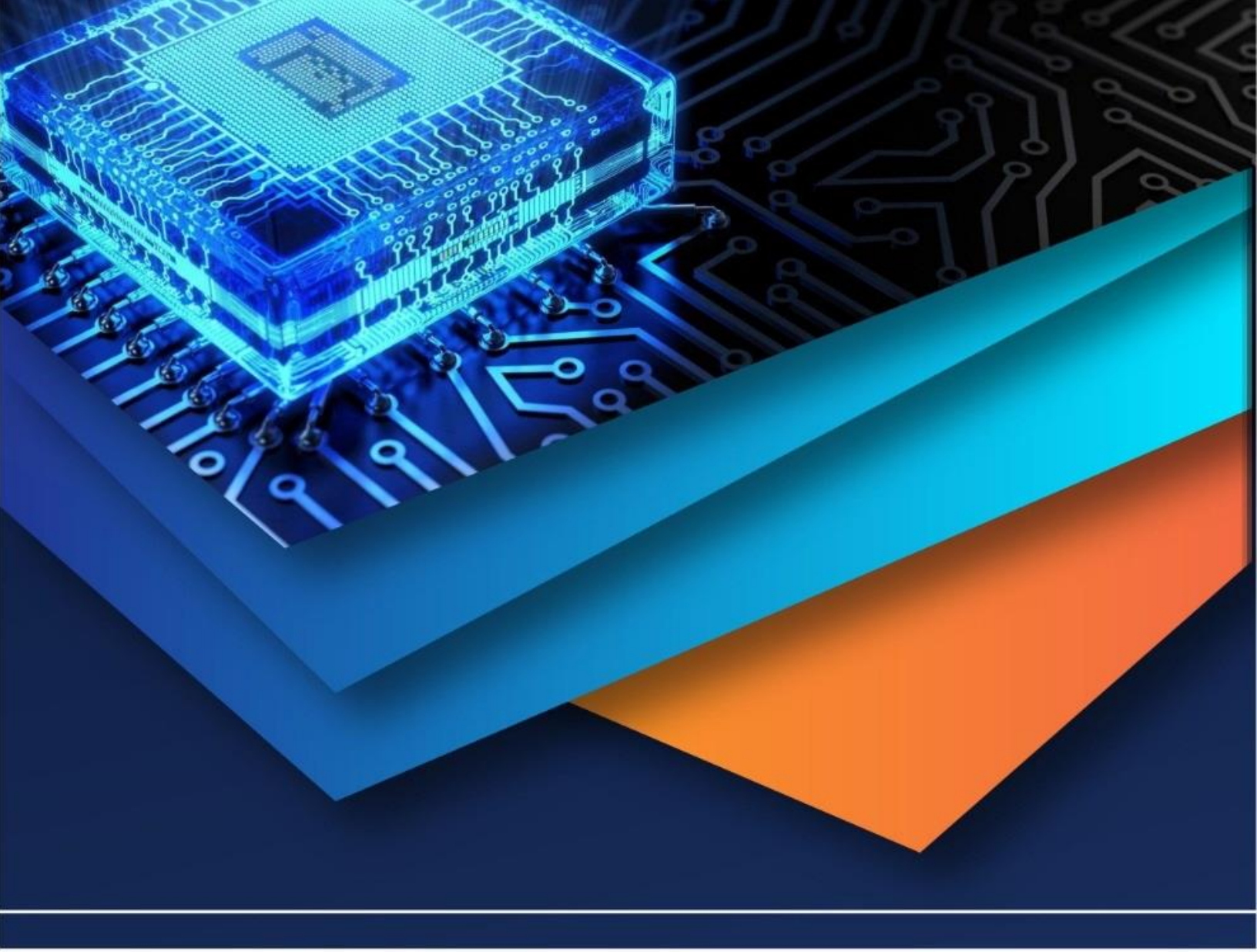
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