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Architectural Design of a Low-Power LoRa-Based Smart Waste Bin Management System

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Abstract: Inefficient waste management, characterized by fixed collection schedules, leads to overflowing bins, unnecessary collection trips, and increased operational costs. This article presents the architectural design of a Smart Waste Bin Management System (SWBMS) engineered to address these challenges through Internet of Things (IoT) technology. The proposed system is built upon a three-tier architecture: the smart waste bin (SWB) node, a LoRa communication network, and a central data monitoring platform. Each SWB is equipped with infrared sensors for fill-level detection and an ATMEGA328P Microcontroller, optimized for low-power operation. A key design feature is the use of MOSFET switches to completely power down sensors and the LoRa transceiver (RFM98) between active cycles, minimizing energy consumption. Communication is handled via LoRa technology for long-range, low-power data transmission to a gateway based on Raspberry Pi and an SX1302-based concentrator. The server layer, comprising a Python UDP application and a real-time monitoring. This design provides an energy-efficient hardware and software architecture for sustainable waste management.
Keywords: Smart Waste Management, Internet of Things, LoRa, System Architecture, Sensor node, Low-Power Design.

I. INTRODUCTION

The management of municipal solid waste is a pressing global challenge, intensified by quick urbanization and population growth. Traditional waste collection methods, which rely on fixed schedules and routes, are fundamentally inefficient. These methods often result in bins beings collected when only partially full, wasting resources, or overflowing before collection, leading to environmental pollution and public health hazards. The advent of the Internet of Things offers a transformative solution by enabling data-driven, dynamic waste management system.

This article focuses on the architectural design of Smart Waste bin Management System (SWBMS) that leverages Low-power wide-area network technology to enable real-time monitoring of waste levels. The primary objective is to detail a system design that is not only functional but also optimized for low power consumption, which is critical for the long-term, battery-operated deployment of such nodes in urban and remote areas. By moving from a schedule-based to need-based collection model, the proposed system lays the groundwork for significant improvements in operational efficiency and cost reduction.

II. LITERATURE REVIEW

Traditional waste management systems follow a fixed-route and fixed-schedule approach, where waste collection trucks visit designated areas at predetermined times irrespective of the actual waste levels in bin. In Côte d’Ivoire, waste collection is done in two different ways.

Fig. 1 Waste accumulation captured in a district of Cote d'Ivoire

Waste is collected by a waste management structure especially in downtown, some municipalities, and the structure generally collects waste disposed in the border of big road. For the zones that are a little bit away from the big road, waste collection is done by individual people, as it is their own business. Waste management structure cannot access some of the zone, because they are easy to access with trucks. So, individual people use such big cart to collect waste, even house by house. Both, waste management structure and individual people follow fixed schedule, regardless of the actual waste accumulation in bins (Fig. 1). This method leads to inefficiencies in fuel consumption, useless collections trips, and overall waste collection operations. Collection trucks may travel long distances to pick up waste from bins that are only partially filled or may fail to collect waste from overflowing bins in time. Another major drawback of traditional waste management is its environmental impact. Frequent truck trips contribute to increased carbon emissions, fuel consumption, and noise pollution. Additionally, waste bins attract pests and contribute to littering, which can create health hazards for local communities. These inefficiencies underscore the need for a more adaptive and data-driven approach to waste collection. The adequate solution for fixing these problems is Technology.

Smart waste management systems utilize IoT-enables sensors, cloud computing, and automated data analysis to enhance waste collection efficiency. In Côte d'Ivoire, there is not an effective solution concerning the smart waste management system, but many solutions have been made in the world. Ashwin [1] developed a smart bin that separates waste based on dry and wet state. When a person approaches the bin, he is detected by an Ultrasonic sensor and open the lib automatically using a servo motor. The smart bin separates dry and wet waste by a capacitive sensor. The whole system is controlled by an Arduino UNO and it's supplied by a battery that collects energy from a solar panel. A warning message is sent to the garbage collector automatically when the waste level is greater than 80%. N. Abdullah [2] talks about IoT-Based waste management system in formal and informal public areas in Mecca. It consists of a waste-gathering approach based on supplying smart bins which can read and convey bin volume data over the internet. Several smart bins are disposed for a specific type of waste such as food plastic and others and a genetic-based optimization algorithm to calculate and find the optimal route to the full waste container. This paper presents another way to segregate the waste using separated container, that can be inefficient for recycling because there is not any system to detect the type of waste. Each smart bins only contains Arduino UNO, Ultrasonic sensor, GPS module and GSM module.

T. J. Sheng [3] implemented an AI-based smart waste management system for real-time waste monitoring and segregation. The system uses LoRa communication protocol to send filling level of the waste, got by an Ultrasonic sensor and location data got by a GPS module in real time. The main processing unit is a Raspberry Pi 3 Model B+ with a TensorFlow framework with a pre-trained object detection model to classify the waste, that detected by a camera connected to the main processing unit. Classification consists of segregate the waste into several compartments including metal, plastic, paper, and general waste using a servo motor. Sohag h. [4] developed a smart IoT based integrated system to alert on time the appropriate authorities when smart bins are full. It consists of a smart bin that continuously monitor the level of waste inside the bin, when it detects full state, a notification is sent using a GSM module [5]. Also, the filled level is display outside on LCD. The whole system is controlled by an Arduino Uno [6]. Zariman [7] is about a smart bin system that send a notification through Blynk. The system is in two parts. A part that monitors the waste level using an Ultrasonic sensor and display it on a Liquid Crystal Display (LCD) for users to let them know about the filling state before they put waste inside. This part is controlled by an Arduino board. The other part is handled by an esp8266 to connect the whole system to Blynk application. Mittal [8] presents an IoT-based smart dustbin that beyond just to detect the level of the waste, is able to detect odors and flame inside the bin. It also considers the weight capacity of the bin and a non-touch interface to ensure hygiene. The particularity of Ganguly [9] work, especially its smart dustbin, is that the lid of the dustbin can be removed without trouble the electric circuit. This smart dustbin has two ultrasonic sensors, to automatically open the lid when something is detected and to measure the level of waste inside. Once high level is detected, Arduino indicate the state outside the dustbin by a Led and when something is detected in this case, the lid stays closed and buzzer alert for an empty action. Chand [10] made a smart bin to be used in a hospital, medical centers, municipalities, households. It is a smart bin based on an Arduino board, that has a non-touch interface handled by a PIR sensor and a servomotor, to automatically open/close the lid of the bin. When the smart bin is full, the microcontroller sends warning an alert message based on level of garbage using GSM module at regular intervals. The system works with very low power and aims to increase the security for front-line workers from the Covid- 19. The detection function is an important, even indispensable part. It's the essential part that gives the garbage can its intelligent appearance. The main sensors for an intelligent waste garbage can are proximity sensors, which are used to measure the level of waste. One of these proximity sensors is the infrared sensor. This sensor consists of an infrared LED that emits radiation, which is passed on when it encounters an obstacle to an infrared receiver that depends on the intensity of the light. This is how it can be used to detect the level of the dustbin [11]. Ultrasonic sensor can also be used for detecting waste level in a waste bin. Many authors have proposed to use ultrasonic sensor for waste monitoring [12, 13, 15]. Addabbo [14] analyses the usability of waterproof ultrasonic sensor for the measurement of waste level inside a trash bin. He said thar ultrasonic sensor used in common off-the-shelf waterproof ranging systems are characterized by a wide radiation lobe, corresponding to an aperture angle up to 70°. So not efficient for a trash bin because it is able to detect the garbage layer top or its position in the. So, this paper made a custom ultrasonic sensor to reduce the detection angle down around 28° to be suitable. Weight sensor [16] also used. The value is the weight of the garbage in the dust bin. Indeed, GPS sensor to is get the current location of a dust bin [17]. RFID is used for garbage identification and also for user identification. And Gas sensor to detect odors [18]. Thamarai M. [19] proposed a self-powered garbage management system using a Convolution Neural Network (CNN) and IoT for households in the context of smart city. The system comprises five modules. Collects households wastes and segregates them into organic and inorganic waste using a CNN. The inorganic wastes collected is sent the recycling bin that contains a IoT-enabled sensor and organic waste is sent to a power generation module where the waste in grinded using a 6combustion unit in the power generator which produce biogas for electric power generation. The system is fully automatic and processed with a Raspberry Pi with the help of sensors and various motors. Muthusamy's paper [20] focused on solar photo voltaic cell waste management. It consists of a IoT-based smart bin utilizing machine learning approach to collect solar waste. The smart bin use k-Nearest Neighbor's algorithm (k-NN) and Long Short-Term Memory (LSTM) that is a network-based learning algorithm, to update the level of the bin via alert messages and to identify the type of waste. The smart waste management systems monitor waste bin levels in real time and use predictive analytics to optimize collection schedules. A. Bhowmik [11] proposed an IoT-based garbage management system considering sanitary problems caused by hazardous garbage in Dhaka, Bangladesh. The system consists of alerting the authority concerned by the admin website, when the bin is 75% filled. There is also user website that help them to find the nearest waste bin. Some are using AI-Based algorithm [21, 22], other are using such software dedicate that can management location and navigation like Google map [17]. Other systems are made for indoor use. W.-T. Sung [23] worked on a smart garbage bin that can move indoor using Indoor Positioning System (IPS) and avoid obstacles thanks to an Ultrasonic sensor and a camera. Haque K. [24] makes an IoT based efficient waste collection system with smart bins which the main purpose is to optimize waste collection using a navigation system that select the best route to collect wastes from the selected bins. The bins are selected by the system from smart bins that monitor a full level state. Sohail H. [25] proposes a solution for the sustainability of waste management. The system contains an intelligent trash bin that send a notification to the authorities when it gets filled or when a fire is detected. The notification is received on a mobile application from the server and waste collector gets navigation to bin's location [26]. A smart bin mechanism for smart cities is proposed in this paper, and it is based on Artificial Intelligent of Things (AIoT) [27]. The smart bin works on 3R concept, that is Reduce, Recycle, and Reuse. Fuzzy Logic is used for decision-making in selecting appropriate in the cities to install the bins [28]. The other part of the system is an efficient waste collection system that checks the status of every trash bin within 500 meters radius of vehicle to optimize waste collection. By this way, the collection will be fast and efficient.

Overall, while significant progress has been made in IoT-based waste management, several gaps remain, particularly in energy optimization, low-cost design. Despite the advancements, a common challenge in many existing IoT-based waste management systems is high power consumption, which limits the operational lifespan of battery-powered bins. Many systems operate with fixed sensing and transmission schedules, leading to unnecessary energy drain. This highlights the need for an energy-optimized system architecture from the ground up. Our design addresses this gap by incorporating hardware-level power management (MOSFET switches) and is designed to support advanced software algorithms for dynamic power control, aiming to significantly extend battery life.

III. SYSTEM DESIGN

The overall architecture of the SWBMS, as illustrated in Figure 1, is a multi-layered system designed for reliability and scalability. It consists of three primary subsystems: The smart waste bin (SWB) unit, which is the edge devices responsible for data acquisition. The central unit, which is responsible to receive data from smart waste bins and transmit them to be monitored. The data monitoring unit, which is the backend server and application for data processing and visualization (Fig. 2). The communication network is a LoRa-based wireless infrastructure for data transmission between smart waste bins and gateway.

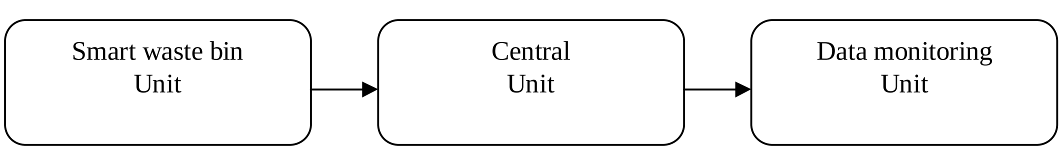

Fig. 2 System architecture

A. Smart Waste Bin Design

The smart waste bin (SWB) is a standard waste bin equipped with sensors and a microcontroller unit. The smart waste bin is equipped with sensors: two sensors on the body for medium and high-level detection. SWB is also equipped of LoRa radio module for data transmission, and ATMEGA328P microcontroller to control everything. The SWB checks the content level at each defined time, and when the medium or high level is reached, this information is transmitted through the LoRa module to warn the municipalities.

The data acquisition unit is managed by two infrared (IR) sensors (KY-032) that are strategically placed at the middle and top of the bin's interior to detect medium and high fill levels, respectively. IR sensors, especially KY-032, are selected for their accuracy and insensitivity to ambient light conditions.

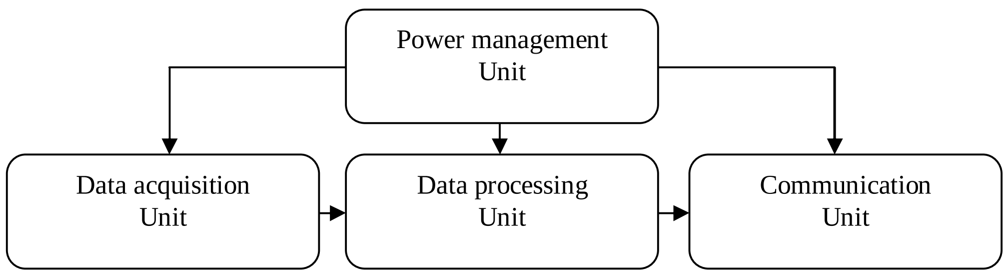

Fig. 3 Smart waste bin architecture

For the communication unit, LoRa radio is used to transmit sensor's data. RFM98 module is used here because, first it matches with the frequency carrier of our region (China) according to LoRa Alliance regulation, and second, it's an energy efficient module. And the whole system is controlled by ATMEGA238P microcontroller. It is cheap and easy to program, also energy efficient.

By the power management part, a critical design innovation for power saving is the implementation of MOSFET transistors (2N7000) as electronic switches. The microcontroller actively powers up the sensors and the LoRa module only during their respective active cycles (sensing and transmission), and powers them down completely during sleep modes. This eliminates standby power consumption, which is a significant drain in constantly powered systems. Fig. 3 shows the complete architecture of the smart waste bin.

The operational cycle of the SWB involves waking from sleep, powering the sensors to check the fill level, and, if a level change is detected, powering the LoRa module to transmit the data before returning all components to powered-down sleep state.

B. Central Unit and Gateway Design

The communication network utilizes LoRa technology for its long-range and low-power characteristics, making it ideal for connecting scattered IoT devices.

Fig. 4 LoRa Gateway (Raspberry Pi + SX1302)

A critical component in any LoRa-based IoT deployment is the LoRa gateway, which acts as a bridge between LoRa end-devices (SWB) and the central network server. Among the various gateway configurations, using SX1302 concentrator in conjunction with Raspberry Pi providers a cost-effective, scalable, and customizable solution. Gateway are passive, meaning they simply receive messages from any node in range and forward them to the network server. The topology of LoRa network is start-of-starts, and the gateway's role is critical because: they receive multiple uplink messages simultaneously (thanks to multi-channel concentrators). The communicate with the network server over IP (Ethernet, Wi-Fi, or LTE). They can cover ranges from 2km in urban areas up to 15km and more in rural areas. This section provides an in-depth explanation of how a LoRa gateway based on SX1302 and Raspberry Pi works, its components, setup, and applications.

C. Server and Software Architecture

The server processes and stores information in a MySQL database. The packets received by the gateway are automatically sent to the UDP app server via UDP protocol. UDP app server decrypts and process all packets, sends message back to the node if needed (downlink), and store node-related information in a MySQL database. The server also hosts a Node JS Rest API for the Web app to manage data. Fig. 5 shows the architecture of the server.

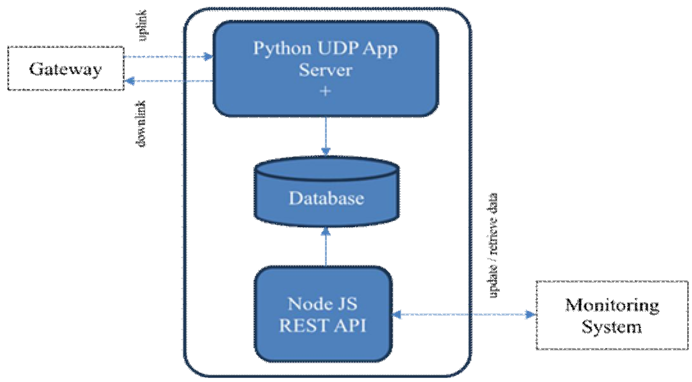

Fig. 5 Server Architecture

The python app is such the processing unit of the gateway, especially for LoRa interface, because the app is entirely responsible of node data. Gateway and UDP App Server communicate permanently together via UDP socket, which allow lightweight and rapid message transmission between of them over an IP network. They communicate with different type of message (Table 1).

TABLE I
UDP Message Type

Type	Direction	Purpose
PUSH_DATA	Gateway to Server	Uplink packet or status message
PUSH_ACK	Server to Gateway	Acknowledge receipt of PUSH_DATA
PULL_DATA	Gateway to Server	Keep-alive to request downlink
PULL_ACK	Server to Gateway	Acknowledge receipt of PULL_DATA
PULL_RESP	Gateway to Server	Contains a downlink packet to transmit

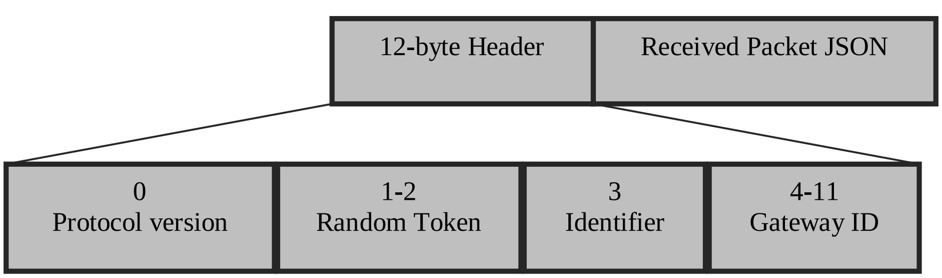

Fig. 6 Uplink frame format

When receiving packet from node, the M-GW1302s concentrator on the gateway demodulates the LoRa signal and forwards the decoded data to the packet forwarder software running on the Raspberry Pi through SPI interface. The packet forwarder wraps the raw payload into a JSON object and sends it to UDP App Server's IP on port 1700 using PUSH_DATA message type. App Server receives the uplink and acknowledges receipt considering the type of message (PUSH_DATA or PULL_DATA). The uplink frame (Fig. 6) contains an identifier byte which represent the message type: 0x00 for PUSH_DATA and 0x02 for PULL_DATA. So, for packets received from node (PUSH_DATA), the app server sends back PUSH_ACK message to acknowledge receipt, and prepare downlink message by decoding received packet (rxpk), that is shown below.


```
{
    "txpk": {
        "imme": false,
        "tmst": 123456789,
        "freq": 433.175,
        "rfch": 0
        "powe": 14,
        "modu": "LORA”,
        "datr": "SF7BW125",
        "codr": "4/5".
        "ipol": true,
        "size": 8,
        "data":"U2VuZCBBY2S="
    }
}
{
    "rxpk": [{
        "time": "2025-10-09707:15:23.1234562")
        "tmst": 123456789,
        "chan": 2,
        "rfch": 0,
        "freq": 433.175,
        "stat": 1,
        "modu": "LORA"
        "datr": "SF7BW125",
        "codr": "4/5"
        "rssi": -45,
        "lsnr": 9.5,
        "size": 12,
        "data":"Q29vbCBEYXRhIQ--"
    }]
}
```


App Server decodes the data field (base64) which contain node data, and send necessary data to the database. Uplink signal is inspected through the ADR algorithm and the result obtain from is taken to create downlink data. UDP App Server creates a JSON message (txpk) containing the downlink data, and this message is sent as PULL_RESP to the gateway's UDP socket. This transmission (downlink) occurs when the gateway sends PULL_DATA message to the App Server to request for downlink message.

The database is strategically made to store significant data to ensure a good waste management. Apart from the waste bin status, each uplink data is stored, especially data rate, RSSI, and SNR value, and all waste bin status update is stored for each SWB. This data will be significant for the improvement of the system and waste management. The structure of the database is described through fig. The server runs “insert” SQL statement to register uplinks in logs table and bin status in bins_status table, but update status field of swb table to change the current status of SWB.

The REST API provides a standardized way for external systems and clients to communicate with the backend database using HTTP requests. It is implemented using Express.js (Node.js). The REST API is specifically used by the web app, to manage smart waste bins, gateways, and to display relevant statistics.

D. Data Monitoring Unit

The frontend interface is developed to provide waste management staff with intuitive controls and visualizations. It displays bin status, location on a map, fill levels, historical trends, and alerts. This interface communicates with the Node.js backend in real-time, ensuring timely decisions and efficient resource deployment. The web dashboard is the administration platform of the system. It allows to manage smart waste bins (register, edit, delete), and manage gateways. The platform also allows to manage users (administrator). The web app is structured into different menus and views. Fig. 7 shows the dashboard view.

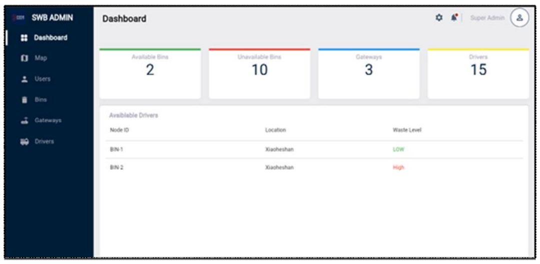

Fig. 7 Web dashboard

IV. CONCLUSIONS

This article has detailed the comprehensive architectural design of a Smart Waste Bin Management System based on low-power IoT principles. The design encompasses the hardware of the smart bin with its innovative power-switching mechanism, the robust LoRa communication network using an SX1302 gateway, and the scalable server-side software architecture. By focusing on energy efficiency at the component level and leveraging long-range communication, this design provides a solid foundation for a practical and sustainable waste management solution.

The next phase of this research, beyond the scope of this article, involves implementing and testing low-power consumption algorithms (such as dynamic scheduling) on the described hardware, deploying the system in a real-world environment, and quantitatively analysing its performance in terms of energy savings and operational efficiency.

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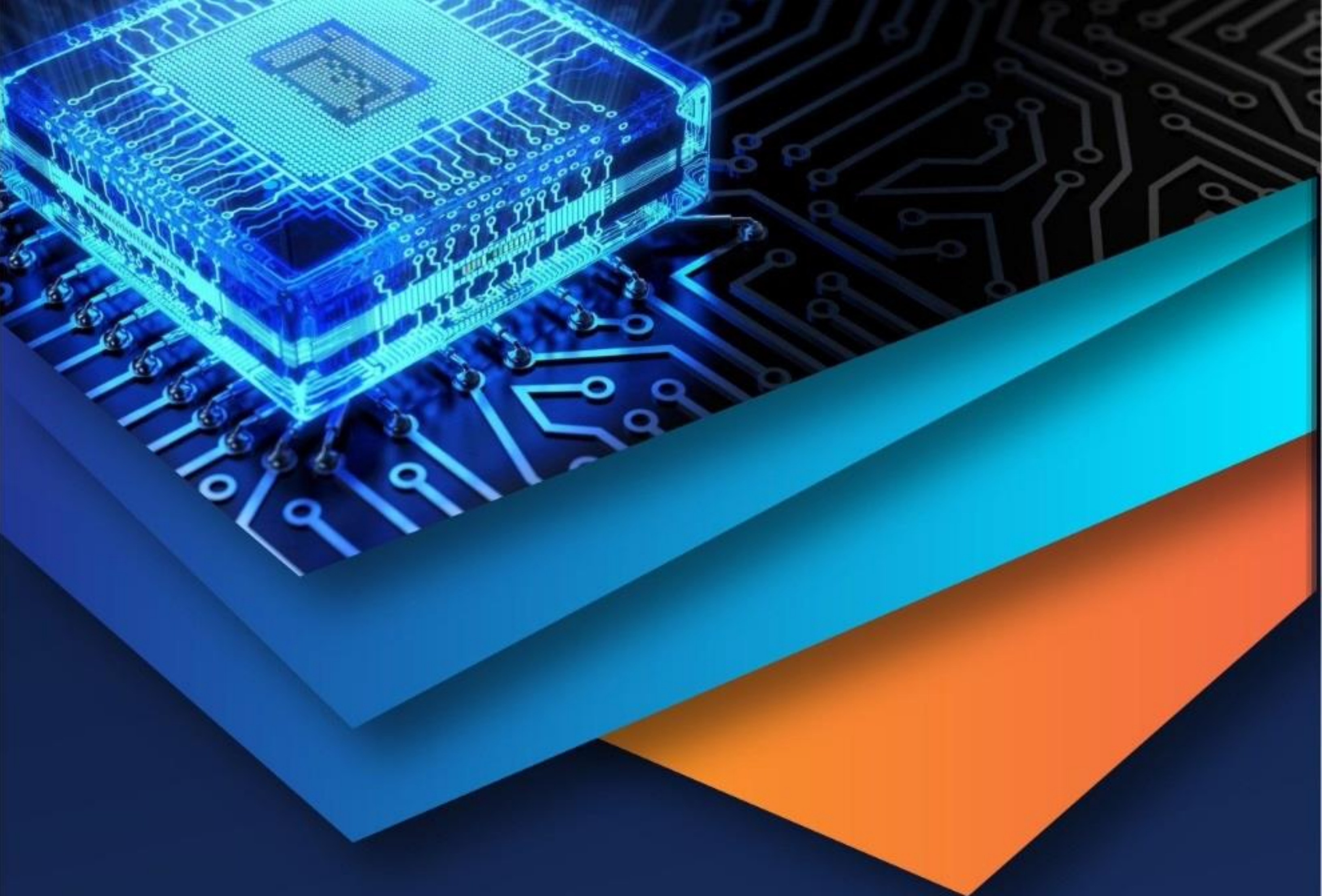

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