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Accessing Physical Document through IoT-Enabled Smart Tagging

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Abstract: Despite rapid digitalization, the storage of documents and files in physical form continues to remain prevalent. With time, the shelves, racks, cupboards or any other medium of storage become cluttered and difficult to manage. Hence, automated tagging of physical documents offers greater flexibility, efficiency, and adaptability compared to traditional manual methods of organizing and searching records. This paper identifies available techniques for tagging physical documents and proposes an Internet of Things (IoT)–enabled automated system for real-time document tracking. By utilizing low-cost hardware components and a scalable system architecture, the proposed model facilitates quick and direct file retrieval, significantly reducing manual effort and search time.

Keywords: Automated Tagging, Internet of Things (IoT), Physical document, Physical Storage, Tracking

1. INTRODUCTION

Physical files such as printed reports, receipts, and logbooks are critical, as they serve as official evidence in audits, legal proceedings, and quality assurance processes. Domains like healthcare, banking, Financial service providers, postal services, government departments, law firms, courts, educational institutions, and many other preserve the structured/unstructured data in physical form.

The government and various official bodies mandates every organization to keep physical copies of their records for a stipulated period of time. Almost in every organization, the data lies in physical forms for various audit purposes and references. In general, how the data is organized physically? Usual trend is pinning the documents in files with descriptive labelling on the file covers. But, the question is, Is this method efficient while accessing the relevant data without hassle? Manual file tracking and retrieval processes are not only time-consuming but also prone to errors, leading to inefficiencies, misplaced files, and operational delays[1,2]. Large Scale organization are capable to invest and manage such data using cost extensive but efficient techniques and technologies. But the system is compromised in Medium and Small Scale organizations that struggles with the funds and competitions to sustain. Responsible personnel are tasked with verifying document completeness, adherence to standardized templates, and proper categorization using color-coded labels, digital labels or self-devised categorization.

The management and retrieval of physical documents[3] in storage facilities present a persistent challenge, especially in dynamic and high-volume environments. Locating physical documents remains a time-consuming task, particularly in large archives. Frequent delays and inefficiencies in retrieving files, especially in the absence of a systematic real-time tracking mechanism is the common scenario in almost every organization.

Recent advances in the Internet of Things (IoT), Artificial Intelligence (AI), and edge-cloud computing are transforming this landscape. Modern approaches aim to build integrated ecosystems where sensor networks, RFID tags, Bluetooth Low Energy (BLE) beacons, and edge devices collectively enable real-time file localization, status tracking, and predictive alerts[4-6]. These architectures are further enhanced by AI models capable of interpreting document metadata, recognizing usage patterns, and supporting intelligent retrieval decisions[7-8].

Despite these innovations, several key limitations persist. Fragmented standards across hardware and communication protocols hinder interoperability[9]. Energy efficiency remains a major concern for battery- operated and embedded devices[10]. Additionally, there is a notable lack of scalable, explainable Artificial Intelligence (AI) frameworks that can provide transparent and auditable decision-making for autonomous document handling[10-11]. As a result, existing systems often lead to confusion, low confidence in the automation, and, in certain cases, redundant development efforts or "reinventing the wheel."

To address these issues, a tagging system that facilitate in direct access to the required file or document is proposed. This study introduces a low cost Internet of Things (IoT)-based solution using NodeMCU ESP8266 modules arranged in a mesh network. This network forms a distributed and fault-tolerant communication infrastructure that connects racks of files to a centralized control system.

The paper is divided into six section. Section 1 lays the foundation of the work further studied for its relevance identifying the need and challenges from the previous research works in Section 2. Section 3 describes the hardware and software utilized to devise a probable solution for automated tagging of physical documents. Section 4 proposes the model designed and illustrates the functional implementation of the model whose viability and significance is discussed in Section 5. Section 6 concludes the work providing the key benefits of the proposed solution and identifying future directions of research.

2. LITERATURE REVIEW

The literature study assembles on automating the identification, organization, and retrieval of physical or unstructured digital documents by interweaving IoT connectivity, lightweight micro-controllers, and AI-driven analytics. Early work on Radio Frequency Identification (RFID) and barcode system[12-14] demonstrated tangible efficiency gains in libraries, hospitals, and warehouses but were constrained by line-of-sight reading and costly hardware. Subsequent studies added wireless intelligence: Use of Message Queuing Telemetry Transport (MQTT) for real-time home communication by[15], mapping the architectural and protocol foundations[9,16-17] enabled later IoT projects to exploit further. Bluetooth Low Energy (BLE) beacons[18] and hybrid BLE-RFID designs[6] extended range and context awareness, yet still lacked visual localization cues.

Node-level innovation accelerated after 2020. Transformers[19] and ESP-based mesh networks[10,20] for resilient document tracking were identified while paired Wi-Fi or LED indicators[17,21-22] with web dashboards, to close the human–machine gap. Mobile-friendly locators built by[23-24] cut retrieval time but relied on centralized clouds, raising latency and scalability issues. Comparative hardware evaluations[25] confirmed NodeMCU's cost advantage, and how mobile robots can extend sensor[26] reach in smart archives.

Concurrent research has focused on content understanding. AI methods used for unstructured document analysis, whereas multiple survey[27-29] highlighted how large language models reshape document automation pipelines. Practical NLP-based product tagging and compared tag- versus folder-based[30] knowledge organization illustrates underscoring usability trade-offs.

Across logistics[31] synthesized automation trends, noting fragmented deployments and piloted IoT library automation that remains limited by the absence of mesh or LED-based cues. Cutting-edge sensor designs, such as the self-powered paper security tag push sustainability and interactivity forward but still face range and durability hurdles. Secure indexing[32] and government-grade RFID tracking is addressed yet without integrating user-friendly localization aids.

The area under study is steadily moving from isolated RFID/Barcode solutions toward integrated, mesh-networked, AI-enhanced platforms that combine real-time visual cues, mobile interfaces, and cloud–edge intelligence[28] to make physical-document retrieval as seamless as digital search.

There remains a lack of fully integrated solutions combining mesh networking, Graphical User Interface (GUI) interfaces, real-time LED localization, and decentralized communication—all of which are addressed in this proposed model.

2.1 Comparison Table: Prior Studies vs. Proposed System

An extensive study of peer-reviewed research papers gave an overview of technologies used for the topic under study. A comparison matrix evaluates the existing system based on key performance indicators such as retrieval speed, accuracy, scalability, ease of integration, power efficiency, and AI integration. Also, the matrix reflects the key benefits of the proposed model in comparison of the existing systems. This strengthens the belief and confidence to carry forward the idea and design the proposed model.

Table 1. Comparative Study of Proposed Model with Prior Studies[17-18, 30-35]

Feature/Criteria	Prior Studies (RFID/BLE/Barcode/IoT)	Proposed System
Real-time Visual Localization	Limited or absent	LED indicators with NodeMCU
Mesh Networking	Rarely implemented	Wi-Fi based NodeMCU mesh network
Editable GUI	Basic or non-existent	Fully editable and user-friendly GUI
Cost-effective Microcontrollers	Some used expensive platforms	NodeMCU ESP8266 (low-cost)
Real-time Feedback Loop	Often delayed or passive	Immediate LED signal upon search
Decentralized Architecture	Mostly centralized	Distributed mesh with fault tolerance
Scalability Tested	Limited rack simulation	Scalable across multiple racks/shelves
Energy Optimization	Rarely addressed	Future scope included
Modular and Maintainable Design	Often static	Modular IoT nodes on racks
Performance Metrics &	Seldom presented	Includes detailed latency mathematical

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Feature/Criteria	Prior Studies (RFID/BLE/Barcode/IoT)	Proposed System
Latency Modelling		model

3. METHODOLOGY

Based on identified gaps, a unified framework is designed that supports the real-time location tracking of the documents. The IoT infrastructure includes: NodeMCU8266, LED, Register, Battery(Rechargeable), Battery Case, Switch and PCB Board. The LEDs can be increased/decreased as per the requirements.

NodeMCU is based on the ESP8266 chip[33], which has native Wi-Fi support. It eliminates the need for external Wi-Fi modules like ESP01 or Ethernet shields. It enables low-cost deployment of multiple nodes in mesh networks or sensor grids. It is suitable in document tracking and is enough for small- to medium-scale control systems like LED-based document indexing. With the support of ESP-NOW mesh control it can efficiently be used in distributed systems for applications like decentralized file search or environmental monitoring.

A mesh Network using ESP-NOW Mesh network protocol to be setup enabling centralized control over distributed LED nodes. One NodeMCU (Gateway) is set as the central controller (Figure 1). This is a super-fast, direct way for NodeMCUs to send small messages to each other without needing a Wi-Fi router. It will provide a robust system for wirelessly managing multiple LED-equipped NodeMCU devices.

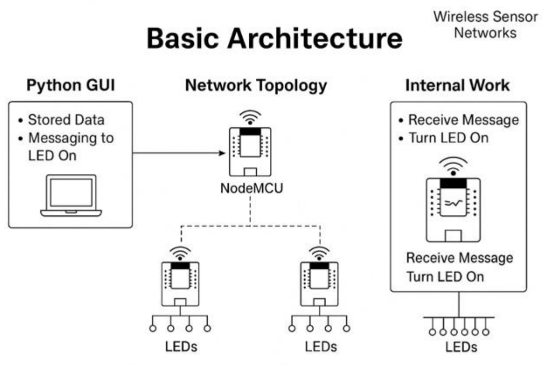
Each ESP8266-based NodeMCU (Remote) is physically installed near or inside the storage units. Upon receiving a command from the central system (through the Python-based GUI (Figure 1)), the NodeMCU activates corresponding LED to visually guide the user to the document's exact location. This immediate feedback significantly reduces search time, especially in environments with a high volume of physical files.

This setup allows the GUI to discover active NodeMCUs, send specific LED commands to any target node, and receive real-time status updates.

3.1 System Overview

Let:

- G: Gateway NodeMCU, connected via USB to PC
- $R = \{R_1, R_2, ..., R_n\}$: Set of Remote NodeMCUs, powered independently



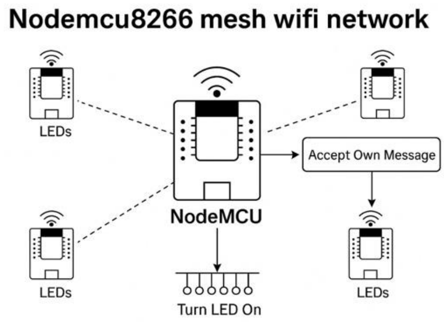


Fig 1: IoT-based Hardware Architecture of Smart-File Tagging

Each node (gateway or remote) controls:

- $L = \{L_1, ..., L_n\}$: LEDs via GPIO pins $D = \{D_1, ..., D_n\}$
- $S^k(t) = \{s^k_1(t), ..., s^k_n(t)\}$: LED state vector of node k at time t
- $k \in \{G, 1, 2, ..., n\}$

3.2 Command Model

Command issued from the Python GUI to the Gateway:

$$C(t)=(N_k,i,a)$$

Where:

- N_k: Target node ID (Gateway or Remote)
- $i \in \{1,...,n\}$: LED index
- $a \in \{0,1\}$: Action (ON = 1, OFF = 0)

The gateway sends N via WiFi using ESP-NOW or mesh protocol. Remote Node parses and updates:

$$S_{ij}(t+1)=\text{Command received from } G$$

3.3 Node Decision Logic

Each node N_k evaluates:

$$\delta_k(C(t)) = \begin{cases} s^k_i(t+1) = a & \text{if } N_k = k \\ \text{Ignore} & \text{otherwise} \end{cases}$$

Gateway Node G:

- If $N_k = G$, it executes LED state change locally.
- Else, it wirelessly forwards the command to the corresponding remote node R_k.

3.4 Wireless Command Propagation

$$\forall C(t) \text{ where } N_k \neq G, \quad G \rightarrow R_k \text{ (via WiFi Mesh)}$$

Remote node R_k applies:

$$s^k_i(t+1) = a \quad \text{upon receiving } C(t)$$

3.5 State Transition Function

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The global LED state at time t is:

$$S\_global(t) = \{S^G(t), S^1(t), ..., S^n(t)\}$$

Given C(t), the updated state is:

$$S\_global(t+1) = T(S\_global(t), C(t))$$

Where T is the composite state transition function for all nodes.

$$s_i = \begin{cases} 1 & \text{if node } n_i, \text{controls rack } r_i = \emptyset(f_i) \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Once the controlling node is identified, it activates the associated LED indicator, denoted as:

$$LED\_i = s\_i$$

3.6 System Latency Model

This activation helps visually locate the correct rack. The total time taken to perform this operation is defined as:

$$T_{total}=T_{db}+T_{net}+T_{led}$$

Where:

- T_{db}: time to retrieve ϕ(fj) from database
- T_{net}: time to transmit signal s_i over the mesh network
- T_{led}: time to activate LED

3.7 Optimization Goal

$$min(T_{total})$$

This represents the optimization goal of minimizing the total time T_{total}, which includes time from database lookup, network communication, and LED activation.

3.8 Scalability & Reliability Constraint

Average latency per node should be within the allowed threshold:

$$L(n) \leq L_{max} \quad \forall n \in N$$

L(n): Load (or tasks/connections) on node n

L_{max}: Maximum allowable load per node

N: Set of all nodes

∀n ∈ N: This condition applies to every node in the network

The system remains scalable as the number of nodes increases, where the load or number of connections each node can handle might be restricted.

Signal propagation probability must remain above a minimum reliability threshold:

$$P(n) \geq P_{min}$$

P(n): The **signal propagation probability** from node n. It represents how likely it is that a message or signal sent by node n successfully reaches its intended destination (such as another node or central controller).

P_{min}: A **minimum acceptable threshold** for signal reliability depending on system requirements.

4 PROPOSED MODEL

The proposed model presents an intelligent system for rapid file retrieval using IoT-based smart document tagging and tracking system. It integrates hardware components, communication protocols, and a user interface to form a cohesive and intelligent document management solution. The microcontrollers are organized into a mesh network, enabling peer-to-peer communication and scalability across multiple nodes.

4.1 Architecture of the Proposed Model

The system is structured around a NodeMCU8266 microcontroller installed as Gateway Server, chosen for its low cost, Wi-Fi capabilities, and ease of integration. Each storage location (e.g., cupboard section, shelf, racks) is equipped with a LED indicator connected to Remote NodeMCU8266(Figure 2).

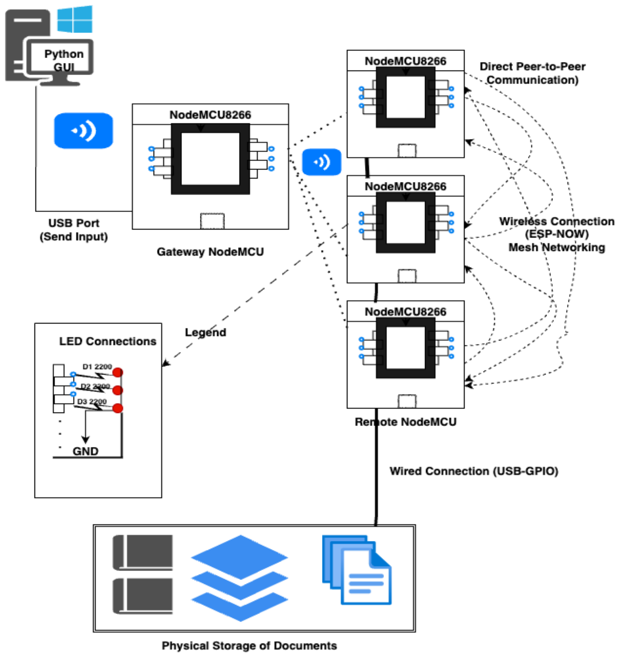

Fig 2: Proposed Model for Smart Tagging of Physical Documents

4.1.1. Gateway NodeMCU:

NodeMCU ESP8266 Board

USB Port: Connect a Micro-USB Cable from the NodeMCU's USB port to an available USB Port on the computer. *(This provides power to the NodeMCU and establishes the serial communication link for the Python GUI.)*

4.1.2. Remote NodeMCU(s) (Wireless Mesh Nodes):

- **NodeMCU ESP8266 Board**
    - **Power Supply:** Connect a 5V Micro-USB Power Adapter (like a phone charger) to the NodeMCU's USB port. *(These nodes are powered independently and communicate wirelessly.)*

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- **LED Connections:** *(These are the LEDs that will be controlled by commands received wirelessly from the gateway NodeMCU.)*

  LEDs (x6):
  - § Each LED's Long Leg (Anode) connects
  - to a 220 Ohm Resistor.
  - § The other end of the 220 Ohm Resistor connects to one of the NodeMCU's Digital Pins(D1...... Dn).
  - § Each LED's Short Leg (Cathode) connects directly to a GND (Ground) Pin on the NodeMCU.

4.1.3. Racks (or any other medium of Physically placed files/documents)

- Each Rack is fitted with Remote NodeMCU ESP8266
- Wired LED indicators are fitted on each shelf for recognizing the relevant area of search.

4.1.4. A Python-based Graphical User Interface (GUI)

Allows the user create the database of the documents/files/books etc. Each document is tagged with a unique ID and associated rack and metadata including name, date, category etc. The user can edit existing records and delete outdated or irrelevant/redundant entries. The server once configured, would communicate with the master NodeMCU (Gateway) using Hyper Text Transfer Protocol(HTTP) or MQTT protocols [6] to transmit control commands.

The GUI serves as the central control hub for the proposed IoT-enabled document tagging and tracking system. It leverages lightweight, open-source libraries such as **Tkinter** (standard GUI package) or **PyQt** (for more advanced UIs), providing a user-friendly and platform-independent interface to facilitate real-time file management and interaction with the IoT hardware.

4.2 Working of the Proposed Model

The serial Gateway connection manages the bidirectional data flow between the Python GUI on the PC and the designated gateway NodeMCU via a serial (USB) connection, handling connection, disconnection, and data encoding/decoding. ESP-NOW Mesh messaging enables direct, fast, and low-power wireless communication between all NodeMCUs in the network, facilitating the exchange of heartbeats and LED control commands without a central router. Node discovery & presence tracking allows each NodeMCU to broadcast its presence (heartbeat) and for the gateway NodeMCU to maintain a dynamic, up-to-date list of all active nodes in the mesh, including their unique identifiers (Node ID, MAC address(Figure 3)).

The active node periodically sends the current list of discovered active mesh nodes from the gateway NodeMCU to the Python GUI, enabling the user to see which devices are online. Command Forwarding & Execution receives LED
control commands from the Python GUI, forwards them via ESP-NOW to the intended target NodeMCU in the mesh, and allows the target NodeMCU to execute the command by activating the specified LED. Non-Blocking LED control manages the temporary activation of LEDs on NodeMCUs using *millis()-based* timers, ensuring that the device remains responsive to other network messages and avoids automatic resets.

The system maps each file fj to a specific rack r_i, controlled by a node n_i, via the mapping function $\phi(f_j)$ **(Eq. 1)**. Once the controlling node is identified, it activates the associated LED indicator LED_i as configured. Once active, i.e. the LED blinks, it helps to visually locate the required file from among the placed racks.

The total retrieval time T_{total} is minimized under the scalability and reliability constraints. With the maximum number of nodes to L_{max} such as latency $L(n) \leq L_{max}$ and transmission reliability $P(n) \geq P_{min}$, the model is believed to remain scalable and optimized.

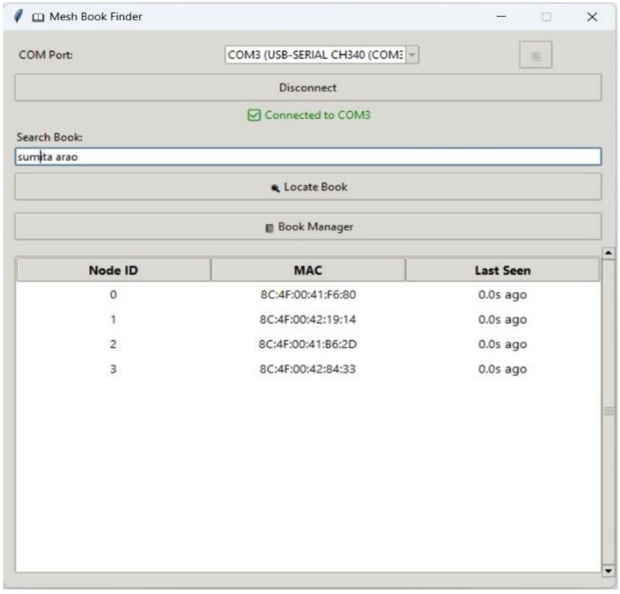

Fig 3: Python-based GUI for real-time file retrieval

5 DISCUSSIONS

An IoT-driven model designed to automate the process of tagging and searching the physical documents in real time demonstrates a novel integration of database querying, wireless mesh communication, and localized LED signalling. The data query is made through Python-based GUI. The prototype claim reduction in search time as compared with manual search, especially where the data is stacked and pile of records lie in unstandardized manner. The use of low-power ESP8266 NodeMCU modules in a mesh network allows decentralized communication, ensuring that signals are efficiently routed even in environments with limited infrastructure. It thereby brings significant advantages over traditional point-to-point or centralized architectures.

The model satisfies the key criteria -efficiency,

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scalability, and robustness, in automating document tracking in environments with high document volume or physical clutter. With quick response time T_{total} and controlled network performance constraints, the architecture supports real-time, reliable responses with minimal delays. The use of NodeMCU ESP8266 devices are cost-effective, Wi-Fi capable and ease to deployment in mesh configurations. It also supports real-time activation of LEDs associated with the file's physical location, improving human-machine interaction and minimizing search effort. This makes the model particularly effective in libraries, warehouses, hospitals, legal archives, educational institutions or any such organization where physical documents are still prevalent and rapid access is essential.

6 CONCLUSION AND FUTURE SCOPE

In-spite of structured labelling of files, locating them from the store house has always been a tedious and cumbersome task. The proposed model offers a scalable, low-cost, and efficient solution to the persistent problem in large or disorganized storage systems. Combination of database-driven logic, mesh communication, and visual cues has benefitted in enhancement of operational efficiency and user experience. The mathematical foundation ensures that performance remains optimal within defined thresholds, balancing speed, scalability, and reliability.

However, the implementation also highlights several critical insights. While the model is functional in a controlled setting, secure communication, node-level errors, backup or parallel setup in case of a failure of controlling node, are few practical concerns that requires further deliberations. Also, the system is limited to implement based on signal propagation in a confined physical location. The need for real-time response places a demand on the system's ability to handle multiple concurrent queries, which can be addressed through future integration of edge computing or lightweight task distribution algorithms.

In essence, the model contributes a modular and extensible architecture that can be deployed with minimalistic effort and complexities. It sets a pathway toward developing a hybrid ecosystem where IoT, embedded systems, and information retrieval coalesce to support faster, more accurate, and user-friendly interactions with physical storage environments. Exploring and incorporating technologies like AI, Computer vision, Robotics would provide much intelligent solutions but also compliment with higher development cost, skills and maintenance. Though, with rising demand and acceptance, these models can be evolved in further research work.

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