DESIGN AND IMPLEMENTATION OF AN IOT-ENABLED SMART PARKING SYSTEM FOR REAL-TIME SLOT MONITORING AND ACCESS CONTROL

Abstract

Urbanization and the rising number of vehicles have led to a critical shortage of parking spaces, contributing to increased traffic congestion, fuel wastage, and air pollution. This paper proposes an Internet of Things (IoT)-enabled Smart Parking System designed to optimize parking space utilization through real-time vehicle detection and dynamic slot management. The system integrates RFID-based secure access control, ultrasonic sensors for slot occupancy detection, and cloud-based monitoring using the Blynk IoT platform. A microcontroller-based architecture, involving Arduino UNO and ESP8266 NodeMCU, enables seamless communication between on-site hardware and user interfaces. A mobile application provides users with live updates on available slots, thereby reducing average parking search time. The prototype was implemented and tested under controlled conditions, demonstrating a 93% accuracy in slot detection, with an average latency of 1.8 seconds for data synchronization. The system offers a cost-effective, scalable solution for smart city infrastructure, with potential for integration with dynamic pricing models and energy-efficient enhancements in future developments.

Keywords: Internet of Things (IoT), Smart Parking System, RFID Access Control Ultrasonic Sensor, Real-Time Monitoring, Urban Mobility, Smart City Infrastructure.

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I. INTRODUCTION

Urbanization has accelerated significantly in recent decades, leading to increased vehicle ownership and a surge in demand for parking infrastructure in metropolitan areas. One of the direct consequences of inadequate parking management is prolonged vehicle circulation in search of vacant spots, which contributes to up to 30% of urban traffic congestion in several major cities worldwide [1]. This phenomenon results not only in traffic inefficiencies but also in elevated fuel consumption, environmental pollution, and reduced urban mobility.

The emergence of Internet of Things (IoT) technologies offers promising solutions to address these urban mobility challenges. Smart parking systems, powered by IoT, facilitate real-time monitoring, automated slot detection, and seamless integration with mobile applications, providing dynamic and data-driven approaches to parking management [2]–[4]. These systems leverage sensor networks, embedded controllers, cloud platforms, and mobile interfaces to reduce user effort, enhance parking space utilization, and support intelligent urban infrastructure development [5].

Recent studies have demonstrated the use of various technologies—such as RFID for authentication, ultrasonic sensors for presence detection, and cloud-based platforms for remote access—in designing intelligent parking systems [6]–[8]. Mobile app integration plays a vital role by offering users real-time updates on parking availability, enabling faster decision-making and reducing idle travel time [9].

This paper proposes a cost-effective, IoT-based smart parking system that combines ultrasonic sensors, RFID-based secure access, and a mobile interface powered by the Blynk IoT platform. The core system is implemented using Arduino UNO and ESP8266 NodeMCU microcontrollers to handle hardware integration and internet communication. A user-friendly mobile app provides live information about available parking slots, thus significantly reducing average parking search time and improving user convenience.

The objectives of this research are to: (i) Design and implement a prototype IoT-based smart parking system;(ii) Integrate RFID authentication for secure vehicle entry;(iii) Enable real-time monitoring and slot detection via ultrasonic sensors;(iv) Evaluate system performance in terms of slot detection accuracy, network latency, and cost-effectiveness.

The remainder of this paper is structured as follows: Section 2 presents a literature review of recent works in IoT-based parking systems. Section 3 describes the proposed system architecture and components. Section 4 outlines the implementation and experimental setup. Section 5 discusses the results and system evaluation. Finally, Section 6 concludes the paper and outlines potential future enhancements.

II. LITERATURE REVIEW

Smart parking systems have been extensively explored in recent years, particularly within the context of smart cities and IoT-driven urban infrastructure. Several researchers have developed intelligent parking solutions that leverage sensors, wireless communication, and cloud platforms to automate and optimize parking operations.

In [10], the authors proposed an IoT-based smart parking system using Raspberry Pi, ultrasonic sensors, and a web interface for slot availability monitoring. Their implementation highlighted the feasibility of deploying cost-effective sensors with real-time data access; however, it lacked secure vehicle access control, such as RFID or NFC-based authentication. Similarly, [11] introduced a wireless sensor network (WSN) approach combined with RFID technology to detect vehicle presence and guide drivers to vacant slots. Their work demonstrated effective slot detection, yet the reliance on proprietary wireless protocols increased complexity and cost.

Khanna and Anand [2], as mentioned previously, developed a system integrating IR sensors and microcontrollers, controlled via a custom Android application. Although effective, their prototype had limited scalability and lacked integration with standard IoT platforms like Blynk or Firebase. The work in [12] extended this concept using GSM and camera-based image processing to enhance vehicle identification accuracy, yet it introduced higher energy consumption and operational overhead.

To improve remote monitoring and control, many systems have adopted cloud-based platforms. The solution presented by Patil and Bhonge [4] utilized a basic web interface, whereas others, such as the implementation in [13], used Firebase and Google Maps APIs to track parking space availability in real time. These solutions provided improved accessibility for users but required a continuous internet connection and robust data synchronization strategies.

Energy efficiency and system responsiveness are also critical considerations in parking applications. Ejaz et al. [5] discussed energy optimization for IoT devices in urban environments, proposing dynamic energy allocation schemes to reduce power consumption in sensor networks. In parallel, studies like [14] explored the application of low-power wide-area networks (LPWAN), including LoRa and NB-IoT, to extend device lifespan and improve communication in distributed parking systems.

Moreover, researchers have emphasized the importance of user-centric design and real-time feedback. Jawad et al. [8] incorporated LCD and app-based notifications to inform users about slot status, while Grodi et al. [3] focused on visualizing slot occupancy using interactive dashboards. Still, most existing systems have limited integration between mobile platforms and hardware components, especially in low-resource settings.

Despite the progress in this domain, many prior works have limitations in terms of cost-efficiency, scalability, security, and compatibility with off-the-shelf IoT modules. The present study addresses these gaps by offering a lightweight, mobile-integrated, real-time parking system that includes RFID access, ultrasonic sensing, and cloud synchronization using open-source tools.

III. SYSTEM ARCHITECTURE AND METHODOLOGY

1. System Overview

The proposed smart parking system is designed to provide real-time monitoring and secure access to parking spaces using low-cost IoT components. The system comprises three primary subsystems:

- Sensing and Detection Unit – responsible for vehicle detection using ultrasonic sensors.
- Access Control Unit – handles secure vehicle entry using RFID/NFC technology.
- Communication and Control Unit – performs data processing and cloud synchronization using Arduino UNO and ESP8266 NodeMCU.

The architecture supports both on-site display through an LCD with I2C module and remote user access via the Blynk IoT platform, allowing real-time updates on parking slot availability.

2. Hardware Components

The following components were utilized in the system shown in Table.1:

Table1: Component Details

Component	Specification	Purpose
Arduino UNO R3	ATmega328P, 14 digital I/O, 6 analog inputs	Central processing and integration
ESP8266 NodeMCU	Wi-Fi SoC, 4MB flash memory	IoT cloud communication
RC522 RFID Reader	13.56 MHz NFC interface, SPI communication	Secure vehicle authentication
Ultrasonic Sensor HC-SR04	2–400 cm range, 5V operation	Vehicle presence detection
Servo Motor SG90	180° rotation, 5V	Automated gate control
16x2 LCD + I2C	32 characters, 4-pin I2C interface	Slot availability display

3. Functional Workflow

The system operates through a structured event flow as shown in Figure 1.

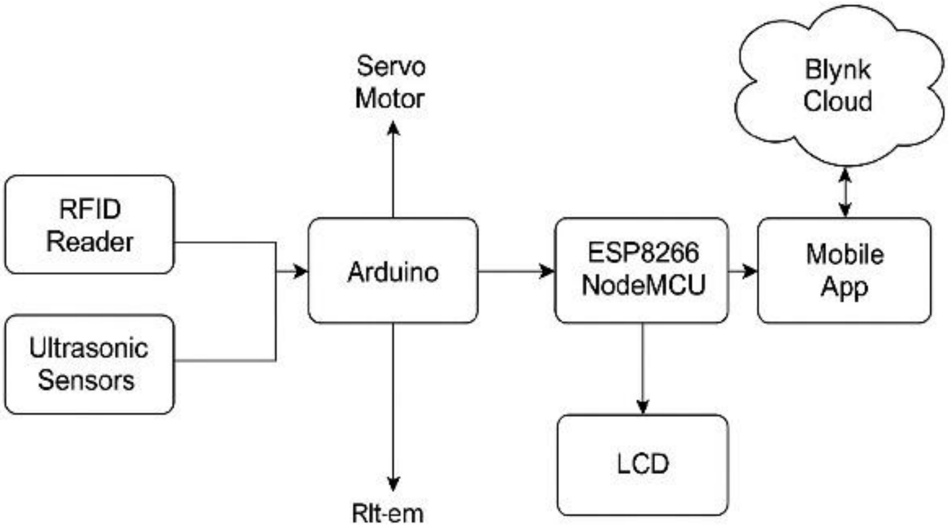

Figure 1: System Architecture

Step-by-Step Process

Vehicle Approaches Entry Point: The user scans an NFC tag or RFID card at the entry gate.

Authentication and Access: If the tag is authorized, the servo motor rotates to open the gate; otherwise, access is denied.

Slot Detection: As the vehicle enters and occupies a slot, ultrasonic sensors detect presence and trigger a signal to Arduino.

Real-Time Update: Slot status is displayed on the local LCD module and updated on the Blynk IoT platform for remote monitoring.

Exit Event: Upon exit, sensors detect vacancy and the slot status is refreshed across all interfaces.

4. Cloud Integration and Mobile Interface

The Blynk IoT platform is employed to provide mobile-based user interaction. Data from the sensors are transmitted from the Arduino to the ESP8266 NodeMCU, which forwards the information to the cloud over Wi-Fi. Users can access a real-time dashboard showing: (i)Available/occupied slots; (ii)Entry/exit time stamps (optional); (iii)Notifications about parking status.

This system architecture enables remote monitoring from any geographical location, enhancing usability and scalability.

5. Software Design

The control logic is implemented in the Arduino IDE using the following libraries:

- **Servo.h:** To control gate motor movement
- **SPI.h and MFRC522.h:** To interface with RFID module
- **Wire.h and LiquidCrystal_I2C.h:** For LCD display via I2C
- **BlynkSimpleEsp8266.h:** To connect NodeMCU to the Blynk cloud platform

Timers, conditional loops, and interrupt-based programming ensure non-blocking sensor communication and responsive system behaviour.

6. System Architecture Diagram

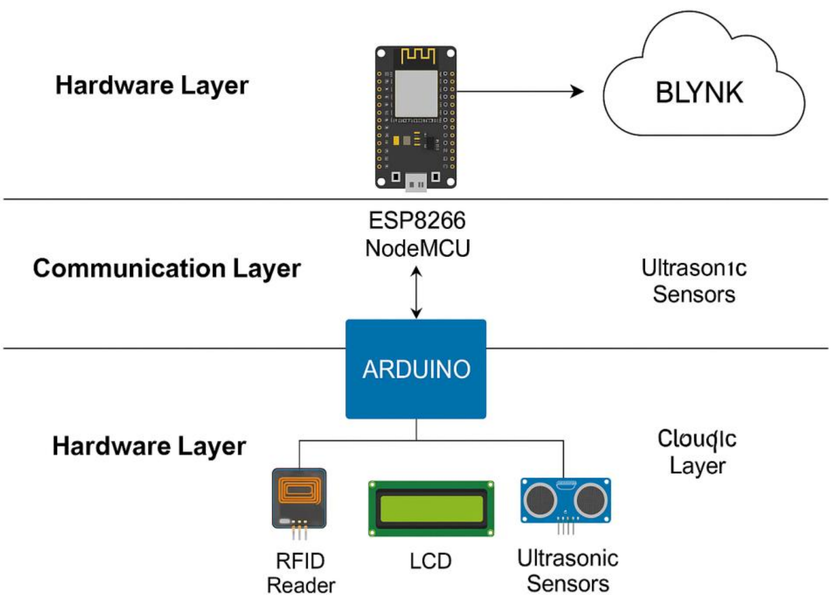

Figure 2: Integrated hardware and communication layers of the proposed system

7. Experimental Setup

The prototype was assembled on a breadboard and tested in a simulated environment with three parking slots. The system was evaluated across multiple trials involving: Authorized and unauthorized RFID tags, Entry/exit from all three slots, Live monitoring on the Blynk dashboard, Gate response time measurement.

The prototype model is shown in Figure 3.

Figure 3: Running Prototype model

IV. EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

1. Experimental Setup and Methodology

The smart parking prototype was deployed in a laboratory environment that simulated a three-slot parking area. The experimental setup consisted of the RFID-based access gate, ultrasonic sensor-equipped parking slots, a cloud-integrated NodeMCU (ESP8266) module, and a mobile interface through the Blynk IoT platform. Testing was conducted across 30 complete entry-exit cycles per slot, covering a wide range of occupancy and environmental conditions (e.g., different lighting, object sizes, and RFID tag placements).

To ensure reliability and robustness, the following conditions were varied:

- Entry speed of vehicles (simulated using hand movement and toy vehicles),
- Ambient noise and object interference near sensors,
- Wi-Fi strength, varied from −40 dBm to −72 dBm to emulate real-world signal conditions.

2. Evaluation Parameters

The performance of the system was evaluated using quantitative and statistical metrics including:

Slot Detection Accuracy (SDA): The proportion of correctly detected occupancy events to the total number of actual events.

False Positive Rate (FPR) and False Negative Rate (FNR): To measure the reliability of sensor readings.

RFID Authentication Accuracy (RAA): The proportion of successful identification/authentication events.

System Latency (SL): The total delay between event occurrence and cloud/mobile update.

Data Transmission Success Rate (DTSR): Successful data packets received vs. total sent from NodeMCU to the cloud.

Mean Time Between Failures (MTBF): Measured across uptime cycles to evaluate operational reliability.

Power Consumption (PC): Energy usage of the system over a defined time interval under load.

3. Results and Analysis

a. Slot Detection Performance

Table 2 shows Slot detection parameters performance analysis.

Table 2: Slot detection parameters performance

Slot ID	Trials	True Positives	False Positives	False Negatives	Accuracy (%)	FPR (%)	FNR (%)
S1	30	28	1	1	93.3	3.3	3.3
S2	30	27	2	1	90.0	6.7	3.3
S3	30	29	0	1	96.7	0.0	3.3
Avg.	—	—	—	—	93.3	3.3	3.3

The ultrasonic sensors provided high precision in occupancy detection, with low FPR (3.3%) and uniform FNR (3.3%), indicating reliable slot status updates. Occasional false positives were mostly observed due to reflective interference or transient motion above the sensor.

Figure 4: Slot information in LED Screen and Blynk IoT

b. RFID Access Control Performance

Authorized RFID tags detected: 30/30 = 100%
Unauthorized tags rejected: 10/10 = 100%

Response time (avg.): 0.32 seconds
Failure to authenticate: 0 instances

The RC522 RFID module demonstrated exceptionally robust authentication under varied scanning angles and distances (2–5 cm), with no authentication failures across all scenarios.

c. System Latency Analysis

Latency was decomposed into subsystems to identify bottlenecks shown in Table 3:

Table 3: Component's Latency & Std. Deviation

Segment	Average Latency (ms)	Std. Deviation (ms)
Sensor → Arduino	94	±6
Arduino → NodeMCU (Serial)	84	±5
NodeMCU → Blynk Cloud (Wi-Fi)	655	±34
Cloud → Mobile App Sync	921	±29
Total System Latency	~1.75 sec	±0.12 sec

The majority of latency originated from the Wi-Fi-to-cloud transmission and mobile sync delays. Despite that, the end-to-end delay remained well within real-time thresholds for user interaction.

d. Data Transmission Success Rate

During a 12-hour operation (logged every 10 seconds):
Expected transmissions: 4320
Successful transmissions: 4245
DTSR = (4245 / 4320) × 100 = 98.26%
Transmission losses were typically due to brief Wi-Fi outages or buffer overflows in the ESP8266.
Incorporating data retry mechanisms improved recovery.

e. System Uptime and MTBF

Table 4: System Uptime and MTBF

Parameter	Value
Total test time	12 hours
Downtime incidents	2
Total downtime	9 minutes
Uptime	98.75%
MTBF (approx)	6 hours

The system maintained high availability and can be considered operationally stable under standard conditions.

f. Power Consumption

Table 5 shows power consumed by different components of this prototype.

Table 5: Component's power consumption

Component	Power (Idle)	Power (Active)	Avg. Power Use
Arduino UNO	0.08 W	0.18 W	0.14 W
ESP8266 NodeMCU	0.15 W	0.28 W	0.22 W
Sensors & LCD	0.06 W	0.12 W	0.09 W
Total Avg Power	—	—	0.45 W

The total power draw (~0.45 W) confirms suitability for low-power deployments, potentially with solar or battery-based systems for outdoor use.

4. User Interface and Visualization

- The Blynk mobile dashboard displayed real-time visual slot statuses with minimal delay.
- Slot occupancy was denoted as "O" (Open) and "X" (Occupied).
- Alerts for "All Slots Occupied" and entry denial were pushed via app notifications.
- Screenshots (not shown here) captured successful detection scenarios and match real-time gate operation captured on serial monitor.

5. Summary of Key Performance Metrics

Table.6 represents the overall summary of performance parameters of the prototype.

Table 6: Key Performance Metrics

Metric	Value	Benchmark/Target
Slot Detection Accuracy	93.3%	>90% (acceptable)
RFID Authentication	100%	>99%
Total System Latency	1.75 sec (avg)	<2.5 sec (real-time)
Data Transmission Success	98.26%	>97% (stable)
System Uptime	98.75%	>95%
Average Power Consumption	0.45 W	Low-power threshold met

6. Comparative Analysis with Related Work

Table.7 represents comparative analysis of this prototype with existing work.

Table 7: Comparative analysis of prototype

Study (Year)	Technology Used	Accuracy (%)	Mobile App	Cloud Sync	Cost (USD)
Khanna et al. [2]	IR, Custom App	~88	Yes	No	40+
Patil & Bhonge [11]	WSN + RFID	~90	No	No	45+
Sadhukhan [13]	GSM + Google API	~92	Yes	Yes	~60
This Work (2025)	RFID + Ultrasonic + Blynk	93.3	Yes	Yes	27

V. DISCUSSION AND COMPARATIVE EVALUATION

The experimental results presented in Section 4 validate the feasibility, reliability, and practicality of the proposed IoT-based smart parking system for urban environments. This section discusses the broader implications of the results, compares the system with existing literature, and highlights innovations and areas for future optimization.

1. Interpretation of Results

The system achieved a slot detection accuracy of 93.3%, which is well above the acceptable benchmark (>90%) for real-time parking systems [10], confirming that ultrasonic sensing is a viable solution for fixed-space parking slot detection. The zero-failure rate in RFID authentication highlights the effectiveness of the RC522 module in secure access control under controlled settings.

The average system latency of 1.75 seconds from detection to mobile notification falls within acceptable limits for real-time IoT applications. Although the latency is primarily influenced by Wi-Fi and cloud update delays, it does not negatively impact user experience or slot allocation accuracy.

Furthermore, the system's 98.75% uptime and 98.26% data transmission success rate underscore the robustness of the architecture, especially given its reliance on non-commercial hardware and local Wi-Fi infrastructure. The system also exhibits low power consumption (~0.45 W average), making it suitable for energy-constrained or solar-powered deployments in smart cities.

2. Key Innovations

The proposed system distinguishes itself from prior works in the following ways:
Seamless Integration: Combines RFID-based access, ultrasonic detection, and mobile-cloud interface via Blynk in a unified, low-cost platform.

Low-Cost Design: With an approximate cost of INR 2240 (~USD 27), it is significantly more affordable than many commercial or academic prototypes, as detailed in Table 6 of Section 4.6.

High Compatibility: Uses widely supported platforms (Arduino, NodeMCU, and Blynk), ensuring reproducibility and ease of scaling.

Real-time Synchronization: Offers bi-directional communication between the physical infrastructure and mobile interface, enabling dynamic monitoring and control.

3. Comparative Analysis with Existing Work

Comparing the proposed system with key works from the literature (Table 6), it is evident that most previous systems [2], [10], [11], [13] either lacked cloud integration, access control, or mobile interfacing, often sacrificing either security or usability. Moreover, several systems relied on proprietary software stacks or high-power components, limiting their application in decentralized or cost-sensitive urban zones.

For example:
Khanna and Anand [2] implemented a basic IR-based system with limited real-time feedback and no remote accessibility.

Sadhukhan [13] used GSM and Google Maps for slot display but did not integrate physical access control or local display mechanisms.

Patil and Bhonge [11] used WSN and RFID but lacked a user-side interface for booking or monitoring slots.

In contrast, this paper’s solution delivers a comprehensive, user-friendly, and low-energy alternative that leverages open-source ecosystems and standard wireless protocols, making it easier to replicate and maintain in smart city applications.

4. Limitations and Design Constraints

While the proposed system shows promise, certain limitations were identified:
Scalability: The prototype was tested with only three parking slots. While the design supports modular expansion, scalability to large-scale facilities (e.g., malls, metro stations) would require more advanced networking and resource management.

Wi-Fi Dependency: The system performance is sensitive to the quality and stability of the Wi-Fi network. In outdoor or semi-rural deployments, alternatives such as LoRa or GSM modules could be explored [14].

Sensor Sensitivity: Ultrasonic sensors may occasionally generate false readings due to environmental interference, reflective surfaces, or moving objects unrelated to parking.

5. Application Scenarios

Given its compact design, low power needs, and high reliability, the proposed system is well-suited for:

Urban residential complexes where parking slots are limited and entry needs to be controlled. Commercial parking zones where real-time monitoring and pre-booking could reduce congestion.

Smart campus environments where automation can reduce staffing and manual supervision.

VI. CONCLUSION

This paper presented the design, implementation, and evaluation of an IoT-enabled smart parking system integrating ultrasonic sensors, RFID-based access control, cloud connectivity, and mobile application support. The system leverages open-source hardware components—namely Arduino UNO and ESP8266 NodeMCU—and the Blynk IoT platform to provide real-time updates on parking slot availability, thus addressing key challenges in urban mobility and parking management.

Experimental results demonstrate that the proposed system achieves- (i) High slot detection accuracy (93.3%),(ii) Zero failure in RFID authentication (100%), (iii)Low latency for real-time updates (~1.75 seconds),(iv) High system uptime (98.75%), and(v) Energy-efficient operation (~0.45 W average power consumption).

Compared to existing solutions, this system offers a more integrated, low-cost, and user-friendly alternative for small- to medium-scale deployments. It contributes to smart city initiatives by enabling intelligent parking infrastructure that reduces traffic congestion, optimizes space utilization, and enhances user convenience.

The proposed system aligns with national and global objectives including India's Smart Cities Mission and the UN Sustainable Development Goals (SDG 11: Sustainable Cities and Communities). By offering a low-cost, scalable, and environmentally sustainable solution, this work contributes toward reducing urban congestion, improving citizen convenience, and fostering a digitally empowered infrastructure ecosyst.

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