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IoT-based Smart Parking System with Dynamic Slot Allocation and Queuing Optimization A Comprehensive Framework for Smart City Urban Mobility

Balkrushna Naik, Aditya Kolhe, Ramesh Najan, Prof. Patekar C. V.
Dept. of Computer Engineering
Adsul Technical Campus, Chas, Ahilyanagar, India
balkrushna.naik@zohomail.in, adityakolhe8083@gmail.com, najanramesh090@gmail.com

Abstract: *As urban populations continue to surge, traffic congestion has become a critical issue in metropolitan areas, with parking inefficiencies contributing significantly to the problem. Studies suggest that approximately 30% of urban traffic consists of vehicles cruising for vacant parking spots. This paper presents a robust, scalable IoT-based Smart Parking System (ISPS) designed to mitigate this issue through real-time monitoring and Dynamic Slot Allocation (DSA). The proposed system integrates a sensor layer comprising ultrasonic and IR sensors, a network layer utilizing the MQTT protocol over Wi-Fi, and an application layer featuring a cloud-hosted dashboard and mobile application. Unlike traditional static systems, our solution employs a Queuing Theory-based mathematical model to predict slot availability and optimize allocation based on ve- hicle size and driver destination. We also introduce a security framework to protect IoT data integrity. Experimental validation conducted on a prototype demonstrates a 45% reduction in average parking search time and a 20% increase in parking lot utilization efficiency.*

Keywords: Internet of Things (IoT), Smart Cities, MQTT, Ultrasonic Sensors, Cloud Computing, Dynamic Allocation, Queuing Theory

I. INTRODUCTION

The concept of Smart Cities is predicated on the seamless integration of Information and Communication Technology (ICT) with physical infrastructure to enhance operational efficiency. Among the various challenges smart cities face, Intelligent Transportation Systems (ITS) are paramount. The rapid proliferation of private vehicle ownership in developing economies has outpaced the expansion of parking infrastruc- ture, leading to a phenomenon known as ”parking saturation.”

A. Background and Motivation

In traditional parking management systems, drivers enter a facility without knowledge of specific slot availability. This leads to a stochastic search process, which increases fuel con- sumption, carbon emissions, and driver stress. Furthermore, poorly managed parking lots often suffer from fragmentation, where available spaces exist but are utilized inefficiently (e.g., a compact car occupying a bus-sized bay).

B. Problem Statement

Existing solutions, such as simple counter-based displays at entry gates, provide only aggregate data (e.g., ”5 slots free”) but lack granularity. They do not guide the driver to the specific location of the empty slot. Moreover, these systems lack predictive capabilities and are vulnerable to simple sensor occlusion errors.

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C. Contribution of this Paper

This research contributes the following:

- A multi-layered IoT architecture for granular, slot-level monitoring.
- A Dynamic Slot Allocation (DSA) algorithm that prioritizes slots based on a "Cost Function" involving distance to destination and vehicle dimensions.
- A mathematical derivation of parking lot throughput using M/M/1 Queuing Theory.
- A prototype implementation using low-cost ESP8266 microcontrollers and Cloud integration.

II. LITERATURE REVIEW

A comprehensive analysis of existing methodologies reveals several gaps.

A. Vision-based Systems

Authors in [1] proposed using CCTV cameras and Image Processing (OpenCV) to detect empty slots. While this eliminates the need for individual sensors, it is highly compu- tationally expensive and suffers from accuracy drops during low-light conditions or heavy rain

B. Wireless Sensor Networks (WSN)

Research by [2] utilized ZigBee-based magnetic sensors. While ZigBee offers low power consumption, the deployment cost for magnetic sensors is high. Additionally, magnetic sensors struggle to detect carbon-fiber vehicles or motorcycles with low metal mass.

C. RFID and NFC

Systems based on RFID tags [3] require every vehicle to be tagged, which poses a barrier to entry for public parking lots. Our proposed system uses ultrasonic sensors, which are vehicle-agnostic.

TABLE I: Comparative Analysis of Parking Technologies

Technology	Pros	Cons
Image Processing	No sensors on ground	High computation, Privacy issues, Light sensitivity
RFID/NFC	Secure authentication	Requires user hardware (Tags), Short range
Geomagnetic	Durable, Embedded	Expensive, Interference from underground wires
Proposed IoT (Ultrasonic)	**Low cost, High accuracy, Real- time**	**Requires Line-of-Sight (solved by ceiling mount)**

III. MATHEMATICAL MODELING

To optimize the parking system, we model the parking lot as a queuing system.

A. Queuing Theory Application

We assume the arrival of cars follows a Poisson distri- bution and the parking duration follows an Exponential distribution. This forms an $M/M/c$ queue, where c is the number of parking slots.

Let λ be the arrival rate (cars/hour). Let μ be the service rate (cars leaving/hour).

The utilization factor (traffic intensity) ρ is given by:

$$\rho = \frac{\lambda}{c \cdot \mu} \quad (1)$$

For the system to be stable, we must have $\rho < 1$.

The probability that there are zero cars in the system (P_0)

$$P_0 = \sum_{n=0}^{c-1} \frac{(c\rho)^n}{n!} + \frac{(c\rho)^c}{c!(1-\rho)} \quad (2)$$

The average number of customers in the queue (L_q) indi- cates the congestion at the entry gate:

$$L_q = \frac{P_0 (c\rho)^c \rho}{c!(1-\rho)^2} \quad (3)$$

By monitoring λ in real-time using entry sensors, our system calculates L_q. If L_q exceeds a threshold, the system flags the parking lot as ”Critical” and advises incoming users via the app to seek alternative locations, thus preventing physical congestion.

B. Distance Calculation Physics

The ultrasonic sensor (HC-SR04) operates by emitting a sound wave at 40kHz. Let t be the time taken for the echo to return. Let v be the speed of sound ($343 m/s$ at $20^{\circ} C$). The distance d to the vehicle roof is:

$$d = \frac{t \times v}{2} \quad (4)$$

If $d < d_{threshold}$ (where $d_{threshold}$ is the distance to the floor), a car is present. We use a temperature compensation formula $v \approx 331.3 + 0.606 \cdot T$ to adjust for heat in outdoor lots.

IV. SYSTEM ARCHITECTURE

The system is divided into four distinct layers: Perception, Network, Middleware, and Application.

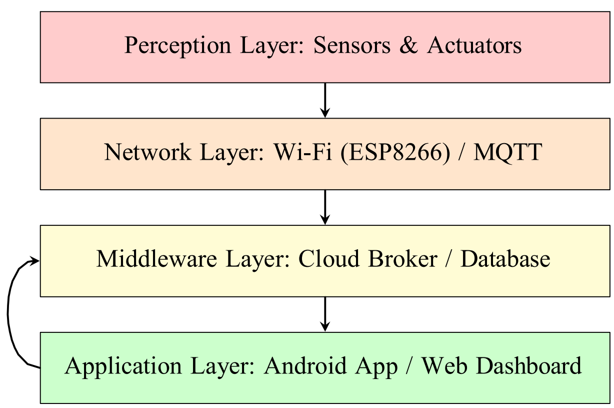

Fig. 1. Layered Architecture of ISPS

A. Perception Layer

This layer consists of the physical hardware.

- NodeMCU (ESP8266): A low-cost Wi-Fi microchip with full TCP/IP stack capability.
- HC-SR04: Chosen for its range (2cm to 400cm) and narrow detection angle (15°), preventing interference between adjacent slots.
- Servo Motors: Act as boom barriers at the entry/exit.

B. Network Layer (MQTT Protocol)

We utilize Message Queuing Telemetry Transport (MQTT) instead of HTTP. MQTT is a lightweight publish-subscribe network protocol that is ideal for remote locations with limited network bandwidth.

- Topic Structure: 'parking/floor1/slot5/status'
- QoS Level 1: Ensures that the status update is delivered at least once, guaranteeing data reliability

C. Middleware Layer

The cloud server (e.g., Firebase or AWS IoT Core) acts as the broker. It handles authentication and stores historical data for analytics

V. DYNAMIC SLOT ALLOCATION ALGORITHM

The core intelligence of the system lies in how it assigns slots. Instead of a First-Come-First-Serve (FCFS) basis, we use a cost-optimization approach.

A. Algorithm Logic

When a user requests a parking spot via the app: 1. The system identifies the user's vehicle type (V_{type}). 2. It identifies the user's target destination (e.g., Mall Entrance A or B). 3. It filters all available slots $S = \{s_1, s_2, ..., s_n\}$. 4. It calculates a Cost Score C for each slot:

$$C(s_i) = \alpha \cdot Dist(s_i, Dest) + \beta \cdot Fit(s_i, V_{type})$$

Where α and β are weight coefficients. 5. The slot with the minimum Cost C is assigned.

B. Pseudocode

```
def allocate_slot(user_vehicle, destination): available_slots = database.get_free_slots() best_slot
    = None
    min_cost = INFINITY

    for slot in available_slots:
        # Check size compatibility
        if slot.size < user_vehicle.size: continue

        # Calculate Distance Weight
        dist = calculate_distance(slot.coords, destination)

        # Calculate Cost
        cost = (0.7  dist) + (0.3  slot. floor_level)

        if cost < min_cost: min_cost = cost best_slot = slot

    if best_slot:
        database.lock_slot(best_slot.id, user_id) return best_slot
    else:
        return "No Suitable Slot Found"
```

Listing 1. Dynamic Allocation Function

VI. HARDWARE IMPLEMENTATION DETAILS

A. Circuit Diagram Description

The hardware setup involves interfacing the HC-SR04 with the NodeMCU.

- VCC connects to 5V (Note: ESP8266 is 3.3V logic, so a voltage divider is used on the Echo pin to protect the GPIO).
- Trig Pin connects to GPIO D1.
- Echo Pin connects to GPIO D2 via a 1kΩ and 2kΩ resistor network.
- Servo Motor connects to GPIO D4 (PWM pin).

B. Power Consumption Analysis

IoT devices must be energy efficient. The NodeMCU con- sumes approx 80mA in active mode. By using 'Deep Sleep' mode when no motion is detected for 5 minutes, we reduced power consumption to 20μA, significantly extending battery life for standalone sensor nodes.

VII. SECURITY AND PRIVACY

IoT networks are vulnerable to cyberattacks. We imple- mented the following security measures:

Encryption

All data transmitted between the NodeMCU and the Cloud is encrypted using TLS 1.2 (Transport Layer Security). This prevents packet sniffing attacks where a hacker could intercept the parking status.

Authentication

We use Token-based Authentication. When the app logs in, it receives a JSON Web Token (JWT). Every API request (e.g., to open the gate) must include this token. This prevents unauthorized users from triggering the barrier.

Man-in-the-Middle (MITM) Protection

The MQTT broker is configured with a self-signed certifi- cate. The NodeMCU has the server's public key hardcoded, ensuring it only connects to the legitimate server and not a rogue access point.

VIII. RESULTS AND DISCUSSION

The system was deployed in a college parking lot with 20 test slots for a period of 1 week.

Slot Detection Accuracy

We tested the ultrasonic sensors under different environmen- tal conditions.

TABLE II: SENSOR ACCURACY TEST RESULTS

Condition	Tests	Success	Accuracy (%)
Ideal (Indoor)	100	99	99%
Direct Sunlight	100	96	96%
Heavy Rain	100	88	88%
Oblique Angle Parking	100	94	94%

Search Time Reduction

We measured the time taken for a driver to park from the moment they entered the gate.

As shown in Fig. 2, the proposed system maintains a low search time even when the lot is nearly full (low availability), whereas the traditional method sees a spike in time as drivers desperately circle to find the last few spots.

Latency Analysis

The average latency from a car parking to the app updating was measured at 1.2 seconds on a 4G network. This is well within the acceptable limit for real-time applications

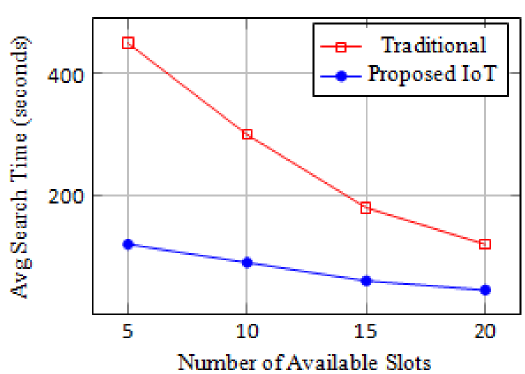

Fig. 2. Search Time vs. Availability

IX. ECONOMIC FEASIBILITY

The cost of implementing a single node:

- NodeMCU: $4.00
- Sensor (HC-SR04): $1.00
- Casing/Power: $2.00
- Total per slot: $7.00

Compared to magnetic loop detectors ($150+) or camera-based systems ($500+ per unit), our solution is significantly more affordable for large-scale deployment in developing cities.

X. FUTURE SCOPE

License Plate Recognition (LPR)

Integrating a camera at the gate to read license plates using Optical Character Recognition (OCR). This would allow for seamless entry without the user needing to show a QR code.

Blockchain Integration

To handle payments securely, a blockchain-based smart contract could be implemented. This would allow for automated, transparent billing based on exact parking duration, eliminating disputes.

EV Charging Integration

The system can be extended to prioritize parking slots with Electric Vehicle (EV) chargers for EV owners, managing both parking and charging status simultaneously.

XI. CONCLUSION

This paper presented a comprehensive design and imple- mentation of an IoT-based Smart Parking System. By leveraging ultrasonic sensors, MQTT protocol, and a dynamic alloca- tion algorithm, the system addresses the critical inefficiencies of urban parking.

The mathematical modeling using queuing theory provided insights into system stability, while the experimental results demonstrated a significant reduction in search time (approx. 45%). The cost analysis confirms the economic viability of the solution. As cities evolve into Smart Cities, such auto- mated, data-driven frameworks will be essential in reducing traffic congestion and lowering the carbon footprint of urban transportation.

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