Smart Parking System for Optimized Vehicle Space Allocation Using Sensors, IoT and Edge AI

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Abstract

The rapid growth of urban populations and vehicle ownership has resulted in severe parking management challenges across metropolitan areas. Drivers often spend significant time searching for available parking spaces, leading to traffic congestion, excessive fuel consumption, increased carbon emissions, and driver frustration. Conventional parking systems rely heavily on manual monitoring and static signage, which lack real-time intelligence and adaptability. This paper proposes a **Smart Parking System for Optimized Vehicle Space Allocation using Sensors, Internet of Things (IoT), and Edge Artificial Intelligence (Edge AI)**. The system integrates ultrasonic and infrared sensors to detect vehicle presence in individual parking slots and utilizes IoT communication to transmit real-time data to a centralized monitoring system. Edge AI is employed to process sensor data locally, enabling faster decision-making while minimizing network latency and dependency on cloud infrastructure. The proposed system provides real-time slot availability information through LED displays and mobile applications, guiding drivers to the nearest available parking space. Experimental evaluation demonstrates high detection accuracy, reduced response time, and improved parking space utilization. The system significantly reduces traffic congestion and parking search time while enhancing user convenience. The proposed architecture is scalable, cost-effective, and suitable for deployment in smart cities, commercial complexes, hospitals, universities, and transportation hubs.

Keywords

Smart Parking System, Internet of Things, Edge Artificial Intelligence, Sensor Networks, Smart City Infrastructure

1. Introduction

Rapid urbanization and the continuous increase in vehicle ownership have significantly increased the demand for efficient parking management systems. In densely populated cities, parking availability has become a major concern for drivers and city planners. Studies indicate that a considerable percentage of urban traffic congestion is caused by drivers searching for available parking spaces. This not only leads to inefficient traffic flow but also contributes to fuel wastage, environmental pollution, and increased stress levels among drivers.

Traditional parking management systems are largely manual or semi-automated. In such systems, drivers must physically search for empty parking spaces, often relying on signboards or parking attendants. These approaches are inefficient because they lack real-time information about parking slot availability. As a result, drivers frequently spend excessive time navigating parking areas in search of vacant spaces.

Recent technological advancements in **Internet of Things (IoT), embedded sensor networks, wireless communication technologies, and artificial intelligence** have enabled the development of intelligent parking management solutions. Smart parking systems integrate sensors, communication networks, and intelligent processing units to monitor parking spaces in real time and guide drivers efficiently.

The concept of **Edge Artificial Intelligence (Edge AI)** further enhances the efficiency of smart parking systems. Instead of sending all sensor data to centralized cloud servers, edge computing allows data processing to occur locally near the data source. This reduces latency, decreases network traffic, and enables faster decision-making.

This research presents the design and implementation of a **Smart Parking System that combines sensor networks, IoT communication, and Edge AI processing**. The system continuously monitors parking slot occupancy and provides real-time information to drivers through digital displays and mobile applications. By optimizing parking space allocation, the system improves traffic flow, reduces fuel consumption, and enhances the overall parking experience.

2. Objectives

The primary objective of this research is to design and develop an intelligent smart parking system that improves parking space utilization, reduces congestion, and enhances driver convenience through the integration of sensor technologies, Internet of

Things (IoT), and edge computing. The proposed system aims to overcome the limitations of conventional parking management systems by introducing real-time monitoring, automated decision-making, and efficient communication between devices and users.

The specific objectives of the proposed smart parking system are described as follows:

1. To design an automated vehicle detection mechanism for individual parking slots

One of the fundamental objectives of the proposed system is to accurately detect the presence or absence of vehicles in each parking slot using sensor technologies. Ultrasonic and infrared sensors are deployed in every parking space to continuously monitor vehicle occupancy. These sensors measure distance and detect obstruction to determine whether a parking slot is occupied or vacant. By implementing automated sensing mechanisms, the system eliminates the need for manual supervision and improves detection accuracy. Reliable vehicle detection forms the foundation for efficient parking management and enables real-time monitoring of parking availability.

2. To develop an IoT-based communication framework for real-time data transmission

Another important objective of the proposed system is to establish a reliable communication infrastructure using Internet of Things technologies. IoT communication protocols such as Wi-Fi, LoRa, or MQTT are used to transmit sensor data from parking slots to microcontrollers, edge devices, and monitoring platforms. The IoT framework ensures seamless connectivity between hardware components and enables continuous exchange of parking data. Real-time data transmission allows parking status information to be updated instantly, providing accurate and timely information to both system administrators and users.

3. To integrate edge computing and artificial intelligence for efficient data processing

The proposed system aims to utilize edge computing techniques to process sensor data locally rather than relying entirely on cloud servers. Edge AI devices such as Raspberry Pi or Jetson Nano analyze sensor inputs and determine slot occupancy in real time. Local processing reduces latency, improves system responsiveness, and minimizes network bandwidth usage. By integrating artificial intelligence algorithms at the edge, the system can filter noise from sensor signals, validate detection results, and make intelligent decisions regarding parking space allocation.

4. To provide drivers with real-time parking availability information

Another key objective of the system is to enhance user convenience by providing drivers with accurate and real-time parking information. The system displays parking availability through LED display boards installed at parking entrances and through mobile or web-based applications. These interfaces show the number of available slots, the status of individual parking spaces, and guidance information to help drivers locate the nearest vacant slot. Providing real-time updates significantly reduces the time spent searching for parking spaces and improves the overall parking experience.

5. To minimize parking search time, traffic congestion, and environmental impact

The proposed smart parking system also aims to reduce the negative impacts associated with inefficient parking management. When drivers spend excessive time searching for parking spaces, it leads to unnecessary vehicle movement, increased fuel consumption, and higher carbon emissions. By guiding drivers directly to available parking slots, the system reduces parking search time and improves traffic flow within parking areas. This contributes to reduced congestion, lower fuel usage, and a decrease in environmental pollution in urban environments.

6. To develop a scalable and cost-effective smart parking architecture

The final objective of the proposed system is to design a scalable and economically viable architecture that can be deployed in various environments. The system uses low-cost sensors, open-source microcontrollers, and flexible IoT communication technologies to ensure affordability. The modular design allows additional parking slots and sensors to be easily integrated without major infrastructure modifications. This scalability makes the system suitable for deployment in large parking facilities such as shopping malls, airports, hospitals, universities, and smart city infrastructures.

3.1 System Architecture

The proposed smart parking system is organized using a hierarchical layered architecture that enables efficient data collection, processing, communication, and visualization. This modular structure allows each layer to operate independently while maintaining seamless integration with other components.

Sensing Layer

The sensing layer forms the foundation of the smart parking system and is responsible for detecting the presence or absence of vehicles in individual parking slots. In the proposed system, **ultrasonic sensors and infrared (IR) sensors** are installed in each parking space to monitor occupancy status continuously.

Ultrasonic sensors operate by emitting ultrasonic waves and measuring the time required for the reflected signal to return after hitting an object. Based on the measured distance, the system determines whether a vehicle is present within the parking slot. Infrared sensors complement this process by detecting physical obstruction through infrared light reflection.

The combination of ultrasonic and infrared sensors improves detection reliability and minimizes false readings caused by environmental conditions such as lighting variations, temperature fluctuations, or surrounding objects. These sensors continuously monitor parking spaces and generate real-time signals indicating whether the slot is **occupied or vacant**.

The sensor nodes are connected to microcontrollers that collect the raw sensor readings and prepare them for further processing. By deploying multiple sensor nodes across the parking area, the system can monitor several parking slots simultaneously and provide a comprehensive view of parking availability.

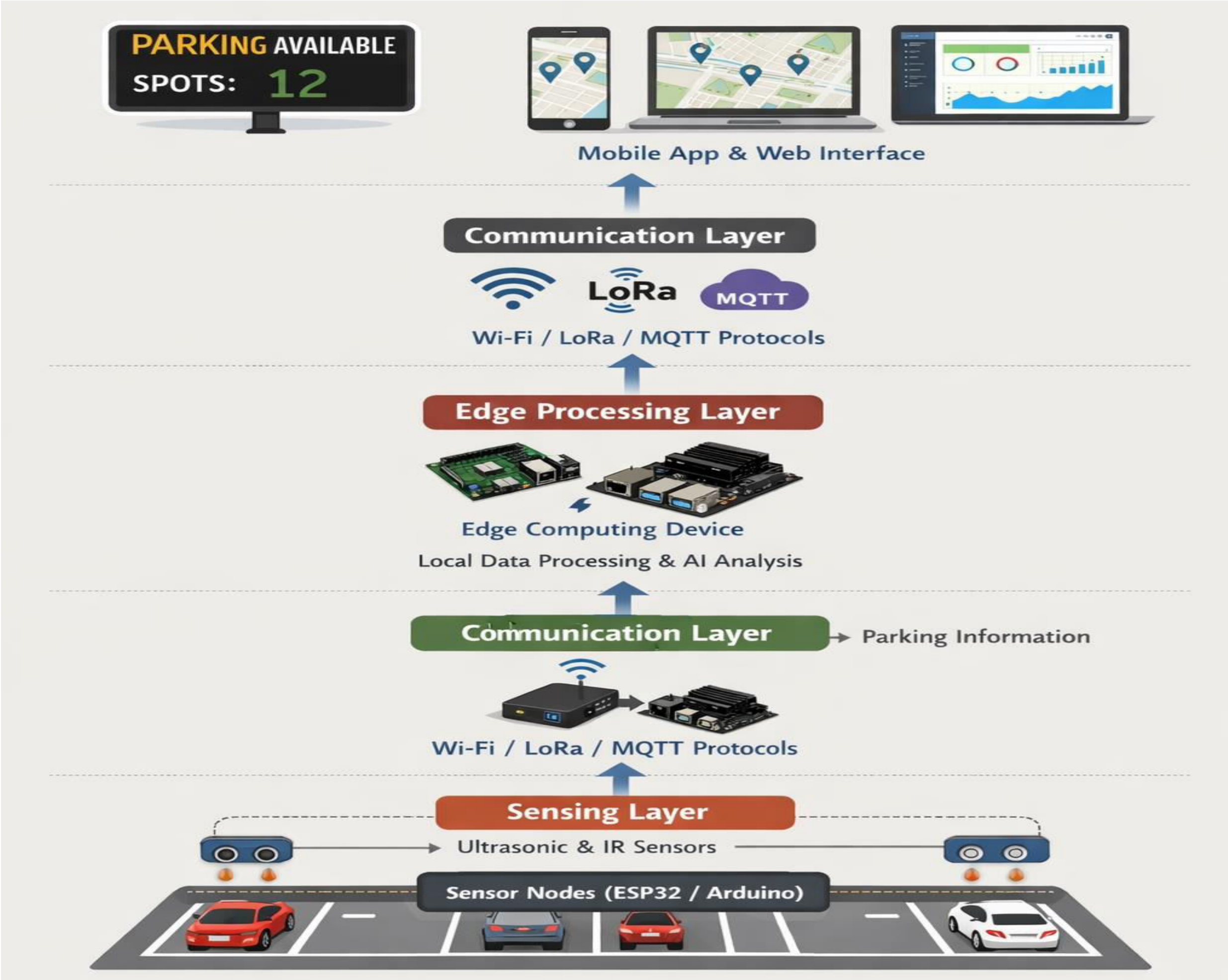

Fig 3.1 Smart parking system architecture diagram

Edge Processing Layer

The edge processing layer is responsible for analyzing the sensor data locally and making intelligent decisions regarding parking slot occupancy. In this layer, a microcontroller such as **ESP32, Arduino, or NodeMCU** receives data from the sensors and performs preliminary processing tasks such as filtering noise and converting analog sensor signals into digital values.

Once the initial processing is completed, the data is transmitted to an **edge computing device**, such as a **Raspberry Pi or NVIDIA Jetson Nano**, which acts as a local processing unit. These edge devices run lightweight artificial intelligence or machine learning algorithms that analyze sensor readings and determine whether each parking slot is occupied or available.

Processing data at the edge offers several advantages compared to traditional cloud-based systems. It reduces latency, minimizes network bandwidth usage, and enables faster response times because the data does not need to be transmitted to distant servers for processing. Edge computing also enhances system reliability in situations where internet connectivity is limited or unstable.

Furthermore, the edge device can perform additional tasks such as anomaly detection, prediction of parking availability patterns, and data aggregation before transmitting summarized information to the central server.

Communication Layer

The communication layer facilitates the wireless transfer of parking data between system components. This layer ensures seamless connectivity between sensor nodes, microcontrollers, edge processing units, and central monitoring platforms.

In the proposed system, **IoT communication technologies such as Wi-Fi, LoRa, or MQTT protocols** are used to enable efficient and reliable data transmission. These protocols allow sensor data to be transmitted in real time from parking slots to edge devices and monitoring dashboards.

Wi-Fi communication provides high-speed connectivity suitable for environments with stable network infrastructure, such as shopping malls, airports, or university campuses. Alternatively, **LoRa communication technology** can be used for long-range, low-power communication in large parking areas or outdoor environments.

MQTT (Message Queuing Telemetry Transport) is commonly used as a lightweight messaging protocol for IoT applications. It allows efficient data exchange between devices while minimizing network overhead. Through this communication framework, parking data is transmitted securely and reliably to the system interface.

Application Layer
The application layer represents the interface between the smart parking system and its users. This layer provides real-time visualization of parking information and enables interaction with the system through digital displays and mobile applications.
Parking availability data processed by the edge device is displayed on **LED display boards installed at parking entrances**. These displays provide drivers with instant information about the number of available parking slots and their locations within the parking facility.
In addition to physical displays, the system also provides **mobile and web-based applications** that allow users to check parking availability remotely. Through these applications, drivers can view slot status, identify the nearest available parking space, and navigate directly to it.
The application layer may also include an administrative dashboard that allows system operators to monitor sensor status, system connectivity, and parking statistics. Historical parking data collected by the system can be visualized through graphs and analytics tools, providing valuable insights for parking management and planning.

3.2 Methodology
The operational workflow of the proposed smart parking system follows a structured sequence of processes, beginning with vehicle detection and ending with user notification. The methodology ensures accurate parking slot monitoring, efficient data processing, and timely communication of parking information.

Fig 3.2 Smart parking system workflow

- **Vehicle Detection**

The first step in the system operation involves detecting the presence or absence of vehicles in parking spaces. Ultrasonic and infrared sensors installed in each parking slot continuously measure distance and detect obstructions within the parking area. When a vehicle occupies a parking slot, the sensor readings change significantly, indicating that the slot is no longer available.

The sensor readings are continuously monitored to maintain up-to-date information about the occupancy status of each parking space.

- **Data Acquisition**

Once the sensors detect changes in parking slot occupancy, the sensor signals are transmitted to the microcontroller. The microcontroller periodically collects readings from all connected sensors and stores them temporarily for processing.

The data acquisition process ensures that sensor readings are collected at regular intervals, allowing the system to monitor parking slots continuously and detect occupancy changes in real time.

- **Signal Processing**

Raw sensor data often contains noise caused by environmental interference or sensor inaccuracies. Therefore, signal processing techniques are applied to filter noise and convert raw sensor readings into meaningful values.

Threshold-based logic is used to determine whether a parking slot is occupied or vacant. For example, if the measured distance from the ultrasonic sensor falls below a predefined threshold value, the system classifies the slot as occupied. This step ensures accurate classification of parking slot status.

- **Edge AI Analysis**

After preprocessing, the sensor data is transmitted to the edge computing device for further analysis. Edge AI algorithms analyze the data to validate sensor readings and confirm slot occupancy status.

Machine learning techniques can also be incorporated to improve detection accuracy by learning patterns from historical parking data. Edge processing ensures rapid decision-making because data analysis occurs locally without requiring cloud-based processing.

- **Data Transmission**

The processed parking data is transmitted through IoT communication protocols to the monitoring system. This communication allows real-time updates of parking availability across display boards and mobile applications.

Efficient data transmission ensures that any change in parking slot status is immediately reflected in the system interface.

- **User Notification**

Once the parking slot status is determined, the system updates LED display boards and mobile applications with real-time parking availability information. Drivers entering the parking facility can easily identify vacant slots and navigate directly to them.

This guidance system significantly reduces the time required for drivers to locate parking spaces.

- **Data Logging and Analytics**

The system also maintains a database of parking activity, storing historical information about parking slot usage, occupancy patterns, and peak demand periods. This data can be analyzed to generate valuable insights for parking management and planning.

Advanced analytics can be used to predict parking demand, optimize space allocation, and improve the efficiency of parking facilities in the future.

4. Proposed System

4.1 System Overview

The proposed Smart Parking System is designed to provide an intelligent and automated solution for managing parking spaces using sensor technologies, Internet of Things (IoT) communication, and edge artificial intelligence processing. The system continuously monitors parking slot occupancy, processes the collected data locally using edge computing, and provides real-time parking availability information to users through digital displays and mobile applications.

The architecture integrates multiple hardware and software components to ensure efficient parking slot monitoring and intelligent space allocation. The main components of the proposed system include:

- **Parking Slot Sensors (Ultrasonic / IR Sensors)**

Sensors are installed in each parking slot to detect the presence or absence of vehicles. Ultrasonic sensors measure the distance between the sensor and nearby objects, while infrared sensors detect physical obstruction in the parking space. The combination of these sensors improves detection accuracy and minimizes false readings.

- **Microcontroller Unit (ESP32 / Arduino / NodeMCU)**

The microcontroller serves as the central control unit that collects data from sensors, processes the raw signals, and prepares the information for transmission. It ensures efficient communication between sensors and the edge computing device.

- **IoT Communication Module (Wi-Fi / LoRa)**

IoT communication technologies enable real-time wireless data transmission between sensor nodes, edge devices, and the central monitoring platform.

- **Edge AI Processing Unit**

Edge computing devices such as Raspberry Pi or Jetson Nano process sensor data locally using intelligent algorithms. Local processing reduces latency and enables faster decision-making compared to cloud-based systems.

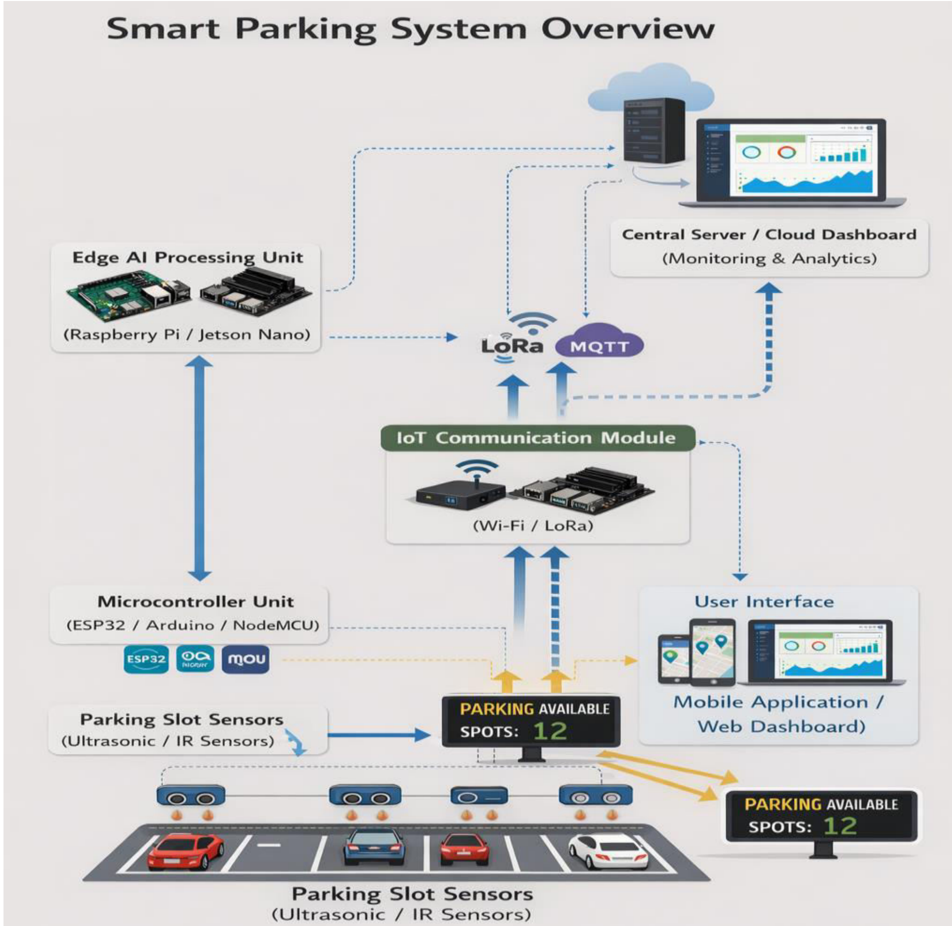

Fig 4.1 Smart parking system overview

- **Central Server / Cloud Dashboard**

The central server stores parking data and provides monitoring and analytics capabilities. Administrators can track parking slot status and analyze historical data for system optimization.

- **User Interface (Mobile Application / Web Dashboard)**

Drivers can view real-time parking availability through mobile applications or web dashboards. LED display boards at parking entrances also provide instant information about available slots.

This integrated architecture ensures efficient parking management, reduced congestion, and improved user convenience.

4.2 Advantages of the Proposed System

The proposed smart parking system offers several advantages compared to conventional parking management systems.

- **Real-Time Parking Availability**

The system continuously monitors parking slots and provides real-time information about available spaces.

- **Reduced Parking Search Time**

Drivers can quickly locate vacant parking slots using mobile applications or display boards.

- **Optimized Space Utilization**

Intelligent slot allocation ensures efficient usage of available parking spaces.

- **Low Latency through Edge AI Processing**

Local data processing reduces delays associated with cloud communication.

- **Reduced Traffic Congestion**

Efficient parking guidance minimizes unnecessary vehicle movement within parking areas.

- **Scalable and Cost-Effective Architecture**

The system uses low-cost sensors and modular design, making it suitable for deployment in large parking facilities.

System Architecture

The proposed smart parking system follows a layered architecture model to ensure modular design and efficient communication between system components.

Sensing Layer

This layer includes ultrasonic and infrared sensors installed in each parking slot. These sensors continuously monitor the presence or absence of vehicles and generate signals representing slot occupancy status.

Edge Processing Layer

In this layer, sensor data is collected by the microcontroller and transmitted to the edge computing device. Edge AI algorithms analyze the sensor data locally to determine parking slot availability.

Communication Layer

IoT communication technologies such as Wi-Fi or LoRa transmit parking data between sensor nodes, edge devices, and the monitoring system.

Application Layer

The application layer provides a user interface through mobile applications, web dashboards, and LED display boards that display real-time parking availability information.

Fig 4.2 Smart parking system infographic

5. Methodology

The methodology of the Smart Parking System describes the operational workflow from vehicle detection to user notification. The system is designed to ensure high detection accuracy, low latency, and reliable communication between system components.

Step 1: Vehicle Detection

Each parking slot is equipped with ultrasonic and infrared sensors that continuously monitor the presence or absence of vehicles. Ultrasonic sensors measure distance, while infrared sensors detect obstruction.

Step 2: Signal Acquisition

Sensor readings are collected by the microcontroller at regular intervals. The controller receives electrical signals from sensors and converts them into digital values.

Step 3: Edge AI Processing

The collected sensor data is transmitted to the edge processing unit. Edge AI algorithms analyze the data to eliminate noise and validate slot occupancy.

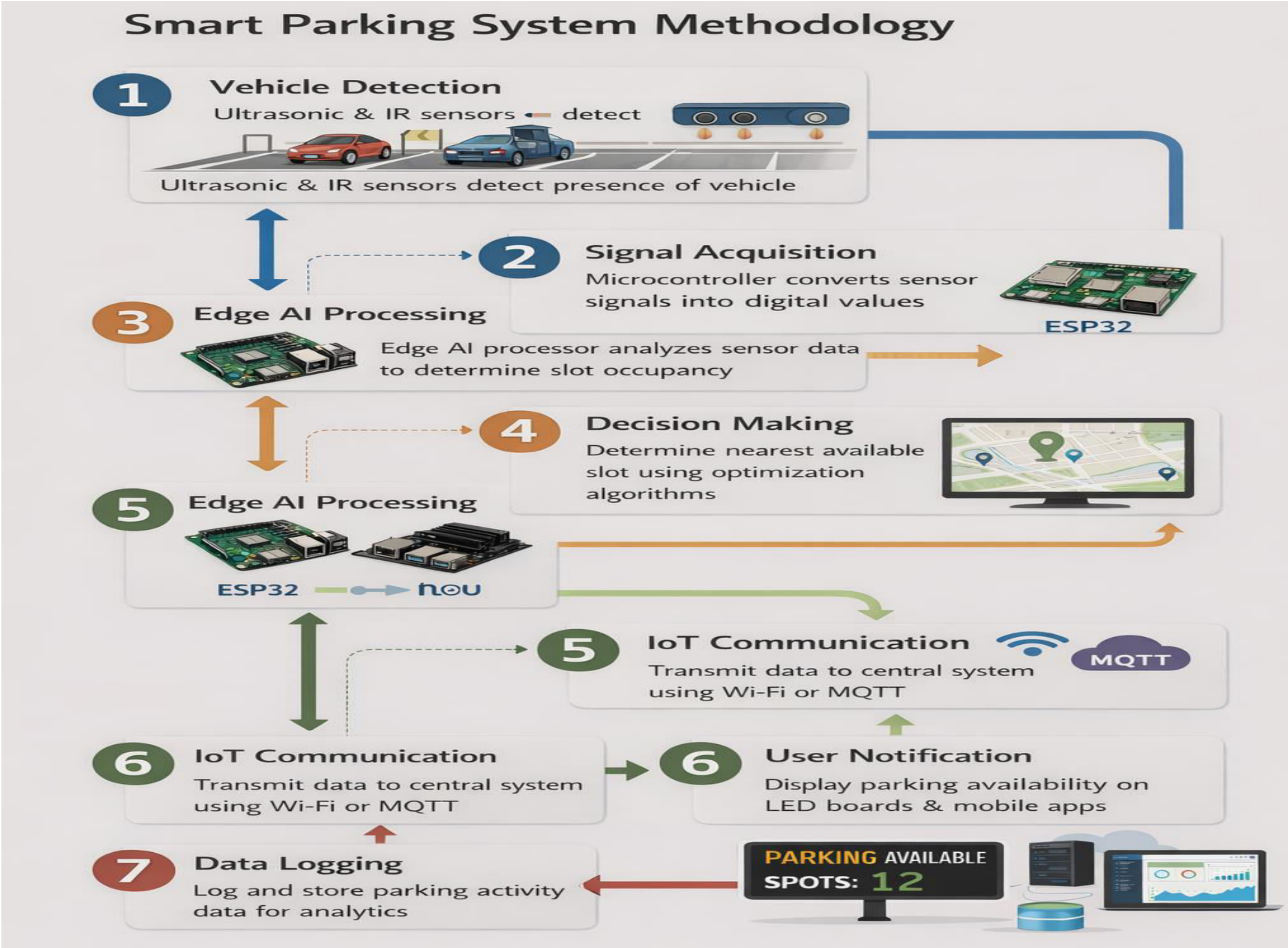

Fig 5.1 Smart parking system flowchart

Step 4: Decision Making
The edge processor determines the nearest available parking slot using distance-based optimization algorithms.
Step 5: IoT Communication
The processed parking data is transmitted to the central monitoring system using IoT communication protocols such as Wi-Fi or MQTT.
Step 6: User Notification
Parking slot availability is displayed on LED display boards and mobile applications.
Step 7: Data Logging
All parking activity data is stored in a database for analytics and prediction of parking demand.
This workflow enables efficient parking space management with minimal delay.

6. Module Description
The smart parking system consists of several functional modules responsible for detecting vehicles, processing sensor data, and communicating parking information.

➢ **Sensor Module**
Ultrasonic and infrared sensors installed in parking slots detect vehicle presence and send signals to the microcontroller.

➢ **Controller Module**
The Arduino or ESP32 microcontroller collects sensor readings and processes raw signals to determine parking slot status.

➢ **Communication Module**
IoT communication modules such as Wi-Fi or LoRa transmit parking data to edge devices and monitoring systems.

➢ **Edge AI Processing Module**
The edge computing device performs local data analysis to determine slot availability and reduce network latency.
Display and User Interface Module
Parking availability information is displayed on LED boards and mobile applications to guide drivers to vacant parking slots.

6.1 Development Environment Setup (Hardware)

The hardware components required for implementing the smart parking system include:

Arduino Uno / ESP32 microcontroller
Ultrasonic sensors (HC-SR04)
Infrared sensors for slot detection
Raspberry Pi 4 or Jetson Nano (Edge AI processor)
IoT communication module (Wi-Fi / LoRa)
LED display board for parking status
Regulated power supply (5V / 3.3V)
Breadboard and jumper wires
USB cables for programming
Smartphone for user interface
Internet router or hotspot for connectivity
Mounting frames for sensor installation
Optional camera module for future AI enhancement

Fig 6.1 Smart parking system infographic overview

6.2 Implementation Phases

- **Phase 1: Sensor and Hardware Integration**

Ultrasonic and infrared sensors are installed in parking slots and connected to the microcontroller. Vehicle detection accuracy and hardware connectivity are verified.

- **Phase 2: IoT Communication and Edge Processing**

Sensor data is transmitted to the edge computing device using IoT communication protocols. Local processing algorithms analyze parking slot status.

- **Phase 3: User Interface and Monitoring**

Parking availability information is displayed on LED boards and mobile applications. Administrators can monitor system status through dashboards.

6.3 Data Flow in Implementation

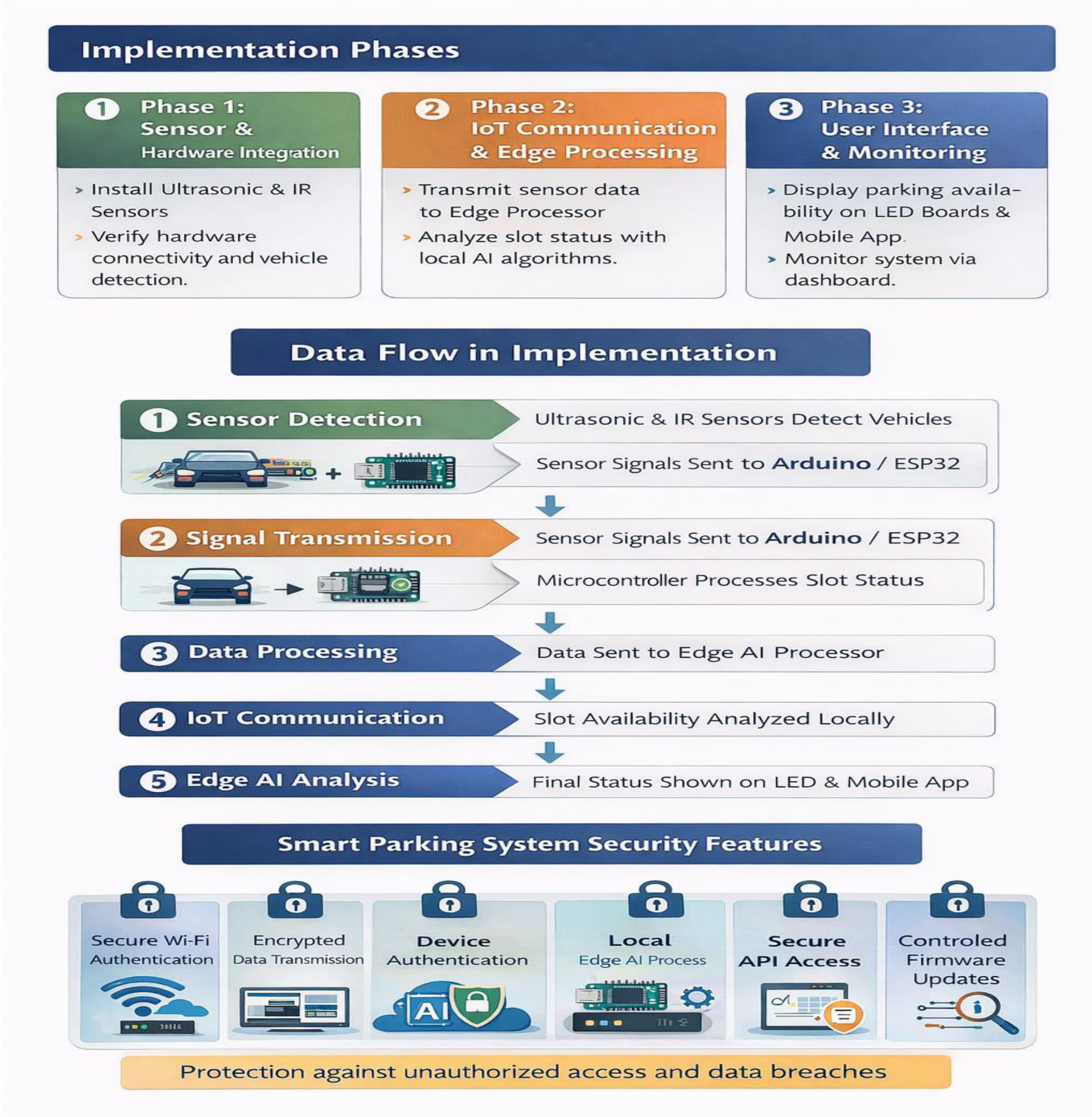

Fig 6.2 Smart parking system implementation infographic

- **Step 1: Sensor Detection**

Ultrasonic sensors measure the distance between the sensor and nearby objects, while IR sensors detect obstruction within the parking slot.

- **Step 2: Signal Transmission**

Sensor signals are transmitted to the Arduino or ESP32 controller.

- **Step 3: Data Processing**

The microcontroller filters raw sensor signals and determines parking slot status.

- **Step 4: IoT Communication**

Processed data is transmitted to the edge AI processor using wireless communication protocols.

- **Step 5: Edge AI Analysis**

Edge computing algorithms analyze sensor data to determine slot availability.

- **Step 6: User Notification**

The final parking status is displayed on LED boards and mobile applications.

6.4 Security Features Implemented

To ensure secure operation of the smart parking system, several security mechanisms are implemented:
Secure Wi-Fi authentication for IoT devices
Encrypted data transmission using MQTT or HTTPS protocols
Device authentication for controllers and edge devices
Edge computing to reduce exposure of sensitive data
Secure API access for mobile applications

Role-based access control for administrators
Protection against unauthorized data modification
Secure firmware updates
Continuous monitoring for abnormal device activity

7. Results and Discussion

The proposed system was tested in a simulated parking environment to evaluate its performance in terms of detection accuracy, response time, and reliability.

Observations

Sensors accurately detected vehicle presence in parking slots.
Parking slot status was updated in real time.
IoT communication remained stable without data loss.
Edge AI processing reduced response delay significantly.
The system successfully monitored multiple parking slots simultaneously.

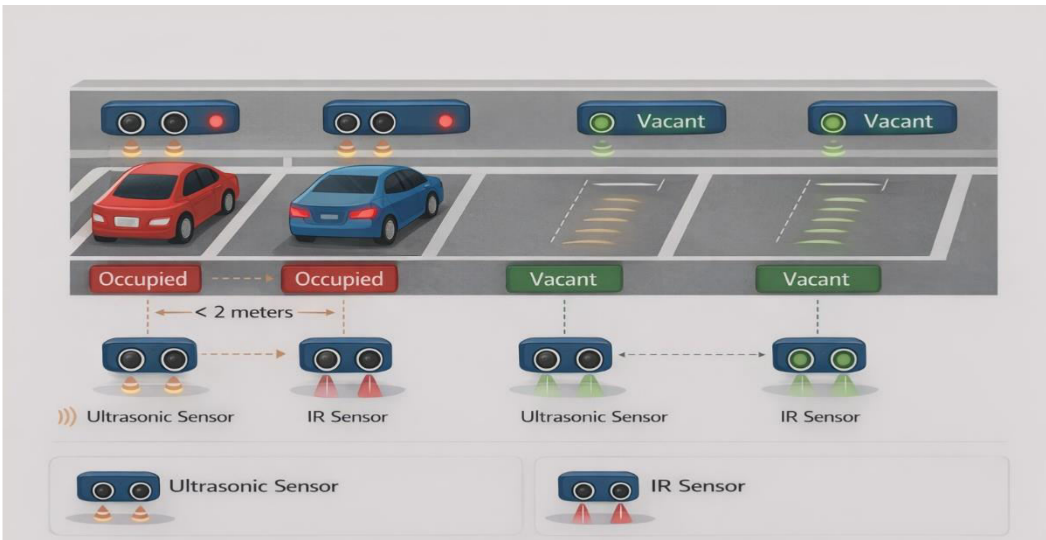

Fig 7.1 Smart parking detection system

Fig 7.2 Driver guidance for parking availability

Fig 7.3 Available parking spots display

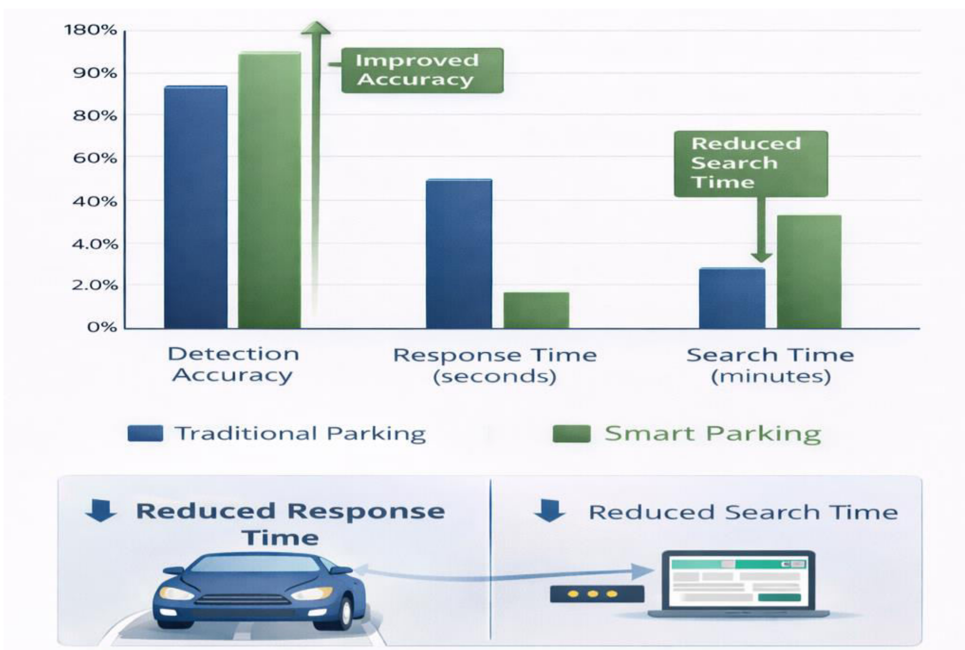

Fig 7.4 Parking system performance comparison graph

- **Test Cases**

Test Case	Input	Output
Vacant slot detection	No vehicle	Slot marked vacant
Occupied slot detection	Vehicle present	Slot marked occupied
IoT communication	Slot status change	Data transmitted successfully
Edge AI processing	Sensor data	Correct classification
Display update	Free slot available	Display shows availability

The system achieved response times below one second, demonstrating efficient real-time performance.

8. Conclusion and Future Scope

The Smart Parking System for Optimized Vehicle Space Allocation using Sensors, IoT, and Edge AI provides an efficient solution for modern parking management challenges. The integration of sensor technologies, IoT communication, and edge computing enables real-time monitoring of parking slots and intelligent allocation of available spaces.

The system significantly reduces the time drivers spend searching for parking spaces, thereby minimizing traffic congestion, fuel consumption, and environmental pollution. Edge AI processing ensures fast decision-making by analyzing sensor data locally without relying heavily on cloud infrastructure.

The proposed system is cost-effective, scalable, and suitable for deployment in smart city environments, commercial complexes, and public parking facilities.

Future Scope

Future enhancements of the system may include:

- Mobile Payment Integration for cashless parking transactions.
- AI-based License Plate Recognition for automated vehicle identification.
- Cloud-based analytics for predicting parking demand and optimizing pricing.
- Solar-powered parking infrastructure for improved energy efficiency.
- Integration with smart city traffic management systems to reduce urban congestion.

These improvements can transform the proposed system into a comprehensive intelligent parking solution for next-generation smart cities.

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