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A Comparative Analysis of Smart Parking Systems: Challenges, Technologies, Innovations and Future Directions

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Abstract: The rapid growth of urban populations has intensified the demand for efficient parking solutions in cities. This Paper presents a comparative analysis of existing Smart Parking Management System challenges and implementation, as well as, it proposes a technique for utilizing the ESP32 microcontroller to optimize parking space usage and reduce congestion. The system leverages IoT technology to detect the real-time availability of parking slots using ultrasonic sensors connected to ESP32 boards. Data collected is transmitted via Wi-Fi to a central server, where it is processed and made accessible through a web or mobile application, enabling users to locate and reserve available parking spaces in advance. The system also incorporates features like automated billing, entry/exit tracking, and integration with navigation systems for user convenience. By providing real-time monitoring and intelligent space management, this ESP32-based solution enhances urban mobility, reduces carbon emissions caused by prolonged vehicle idling, and contributes to the development of smart city infrastructure.

Keywords *Smart Parking, Smart Cities, Wireless sensor networks (WSN), Internet of Things (IoT), Arduino, ESP32, Radio Frequency Identification (RFID), Sensors, Urban Mobility*

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I. INTRODUCTION

Cities are facing challenges in parking availability and a decline in quality of life due to rising car ownership rates and increased carbon emissions [2]. Parking Management System can be classified into three amin categories; Manual System, Semi-Automatic System and Automatic Systems as illustrated in Figure 1. The Internet of Things (IoT) is opening the door for essential smart city applications, especially The Smart Parking Management System (SPMS) [1].

Smart parking solutions are unavoidable given the expanding population, especially in cities. The most individuals choose to use private transportation instead of the public transportation because it's more convenient, something that many of us have entrenched in our daily lives, which increases the number of cars on the road and, consequently, traffic [3, 5].

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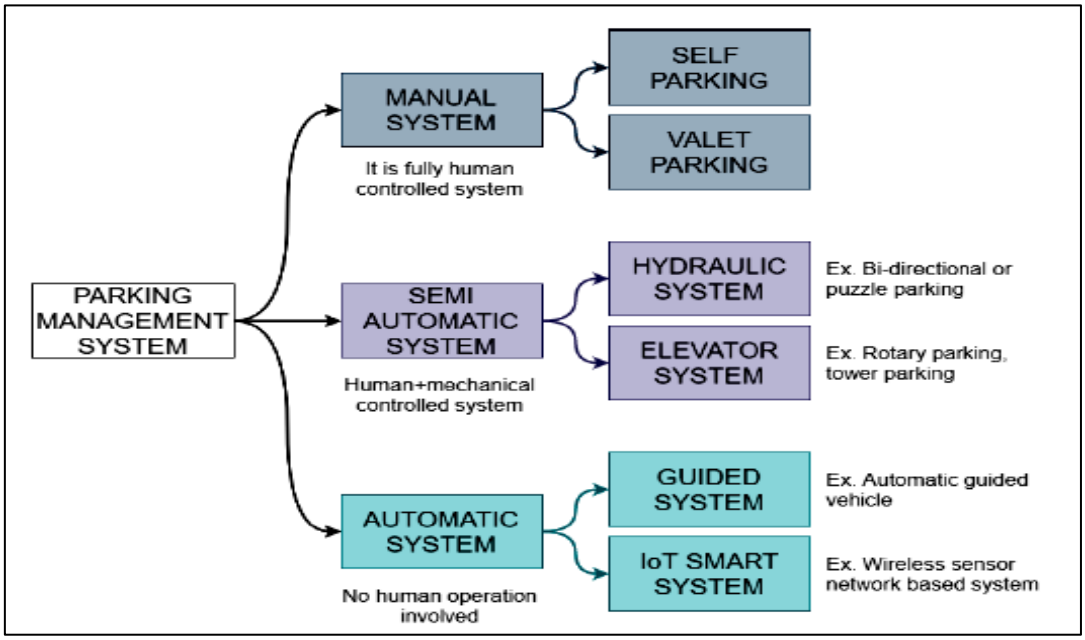

Fig 1: Parking Management System Classification [6]

Finding a parking space in crowded towns and cities is a difficult task that wastes time, uses unnecessary fuel, and most importantly—contributes to climate change. The problem of parking is so important that it has come up in both political and climate change mitigation talks [2].

The rising number of vehicles in urban areas necessitates innovative parking management solutions. Traditional parking systems fail to address the challenges of real-time space availability and traffic congestion. Smart Parking Management Systems (SPMS) leverage various technologies to enhance parking efficiency, reduce search time, and lower emissions [4].

This paper offers a comprehensive review of Smart Parking Management Systems SPMS challenges, technologies and presents a practical implementation using Arduino ESP32 and Python.

II. RESEARCH BACKGROUND

Smart Parking Management Systems use IoT sensors, real-time communication, and mobile apps to streamline the parking experience. Despite their advantages, numerous technical, infrastructural, societal challenges and Environmental and Physical Constraints hinder widespread adoption and functionality [7] as shown in Figure 2.

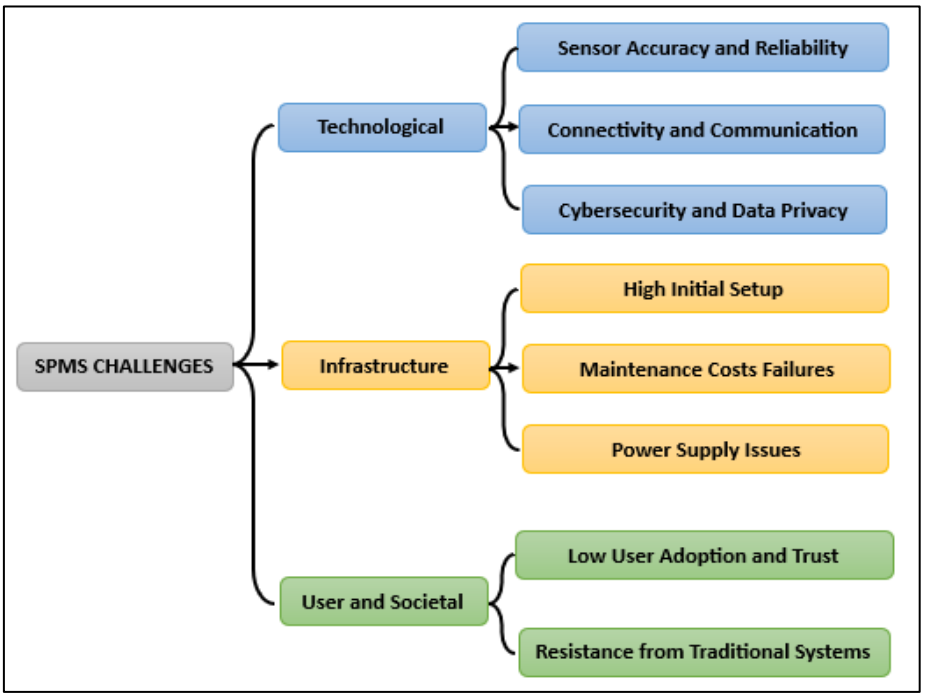

Fig 2: Smart Parking Management System Challenges

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Sensor Accuracy and Reliability, Connectivity and Communication Failures and Cybersecurity and Data Privacy are the main technical challenges Smart parking Management System Face it. Sensors (such as infrared, magnetic, and ultrasonic) constitute the foundation of SPMS. However, weather-related factors like rain, snow, or dirt can make them less accurate. Inaccurate availability reporting due to misreadings might undermine user trust [8].

An infrared sensor (IR sensor) is an optoelectronic component that is sensitive to radiation and has a spectral sensitivity in the 780 nm to 50 μm infrared wavelength range. There are two types of IR sensors, Active infrared sensor and passive infrared sensor [8].

The Active Infrared (AIR) Sensor produces infrared light and picks up the light reflected from nearby objects. Light Emitting Diode (LED) and receiver are the two parts of the active infrared sensor. A receiver picks up reflected infrared radiation from an LED. Rain and snow might affect an active infrared sensor [8].

No infrared radiation is emitted by a passive infrared (PIR) sensor. Rather than that, it senses variations in the radiation from its environment. PIR sensors are mostly employed for object detection. It is mostly employed in SPMS for parking lot occupancy detection. The PIR sensor, like the AIR sensor, is susceptible to changes in the environment, including snow and rain [8] [9].

Continuous data transfer is essential to IoT-based parking systems. Parking data's real-time availability is impacted by network outages (such as those that occur in heavily populated regions) [10]. Given the rise in cyberthreats, the gathering of user data (such as location and payment information) raises questions regarding data abuse and security breaches [11].

High Initial Setup, Maintenance costs and Power Supply issues are the most infrastructure challenges of SPMS; where it costs a lot to install and maintain Smart Parking Systems networks and devices. Installing sensors along the side of the road or underground is very costly [12]. As well as, It might be challenging to guarantee that sensors and gateways have a steady power supply, particularly in outdoor settings. Devices that run on batteries need to be serviced frequently because their lifespan is limited [13].

One of the primary challenges for Smart Parking System based on wireless sensor networks is building fully connected networks with low power consumption sensors, devices, and protocols. This is particularly true in locations where ordinary wireless network establishment is challenging, like historical districts, archaeological sites, and so on [14].

The majority of the technical and infrastructural issues with smart parking systems have been resolved in recent years as a result of the quick advancement of technology. However, Low user Adoption, Trust, lack of knowledge and Resistance from the Traditional Parking Systems remain the primary obstacles to the spread of Smart Parking systems [15].

Due to inexperience, apparent complexity, or mistrust of technology, many consumers are still ignorant of or hesitant to use SPS. Usability is further diminished by a poorly designed user interface and a lack of standardization. In addition to, Integrating SPS with the traditional urban parking policies and legacy systems poses political and bureaucratic barriers. Coordination between private and public sectors is often lacking [15].

III. RESEARCH METHODOLOGY

In Egypt and other similar countries, the traditional parking system in urban area's environment causes traffic and parking inefficiencies for citizens and governmental. Smart Parking Management system can be used to address this issue, in addition to controlling traffic and removing arbitrary parking, governments can employ Smart Parking Systems as a reliable source of national revenue for street upkeep and cleanliness. Using electronic wallets and Payment applications such as InstaPay application can simplify the process of parking payment.

In this research, we propose a simple design for implementing a smart parking system that is compatible with existing infrastructure in urban environments, without restructuring cities, while preserving the historical form and original identity of the cities as illustrated in Figure 3. Instead of using conventional parking techniques, the suggested design parks automobiles on pavement segments, generating revenue that may be utilized to keep the city and its streets clean and maintained. Conventional sidewalks can be converted into smart parking systems using simple Ultrasonic sensors, Arduino and ESP32 microcontrollers and Gateways that can be fastened to the lighting poles.

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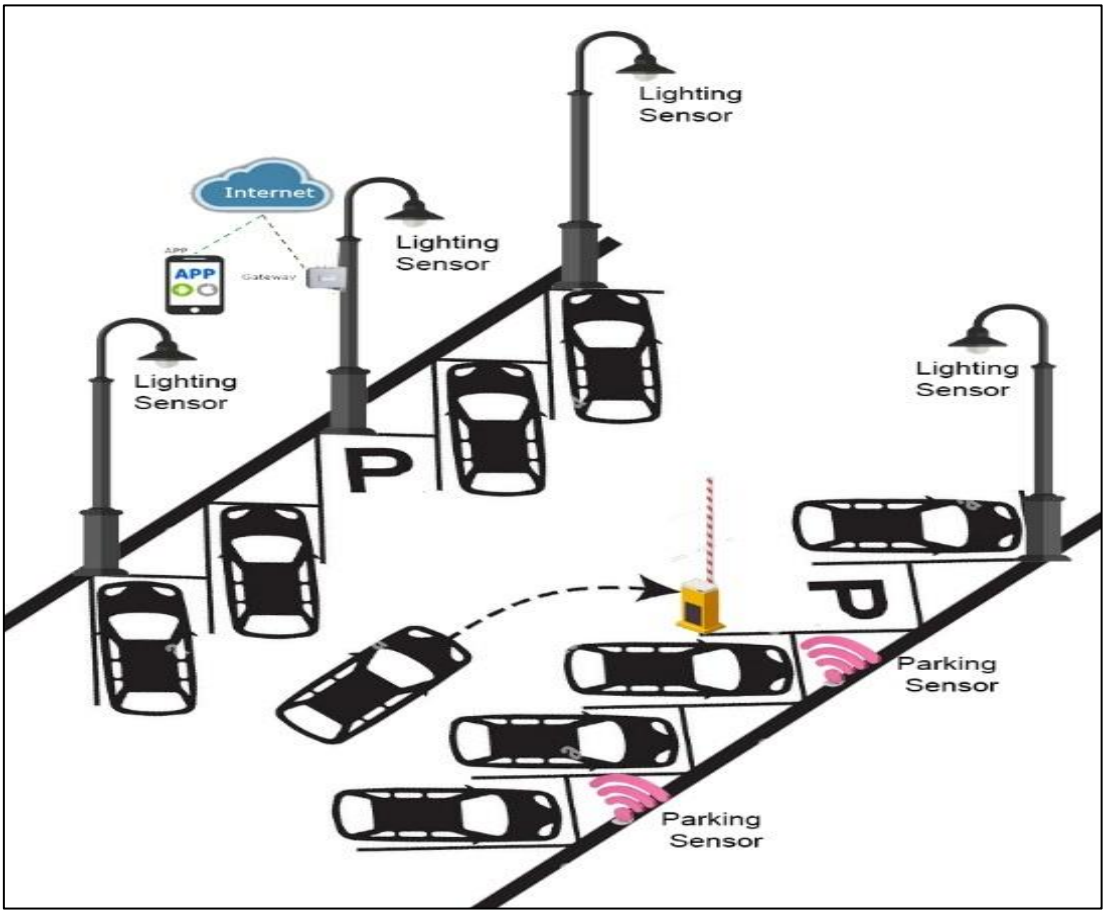

Fig 3: The Proposed Architecture of Smart Parking Management System

The Smart Parking Management System based on ESP32 microcontroller. ESP32 offers an effective, low-cost, and scalable solution for modern urban parking challenges. Utilizing the ESP32's built-in Wi-Fi, Bluetooth, Bluetooth Low Energy (BLE) and ESP-Now protocols capabilities, the system enables real-time monitoring and communication between parking sensors and a centralized server or mobile application.

By deploying sensors connected to ESP32 units in individual parking spots, the system can detect vehicle presence accurately and transmit data instantly. This real-time availability information helps drivers locate vacant spots quickly, reducing traffic congestion, fuel consumption, and time spent searching for parking.

Integrating Mobile Application with The ESP32-based smart parking system can offers real-time parking availability, reducing time spent searching for spots and easing traffic congestion. It enhances user convenience. The system is cost-effective, energy-efficient, and scalable for smart city applications. Moreover, the system supports remote management, data logging, Low Energy consumption and automated alerts, making it suitable for smart city integration. Its modular design allows for easy expansion and customization to meet specific requirements of different locations, such as malls, campuses, or public parking areas.

IV. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The Smart Parking Management System offers a modern, innovative and efficient solution to one of the most persistent urban challenges—parking congestion. By leveraging technologies such as IoT sensors, real-time data processing, and user-friendly mobile interfaces, the system significantly enhances the parking experience for both drivers and administrators. It reduces the time spent searching for parking spaces, minimizes traffic congestion, and optimizes space utilization. a wide range of technical, economic, societal, and environmental challenges had been addressed through this paper to ensure scalable and sustainable implementation.

The implementation of such a system promotes sustainability by lowering vehicle emissions and supports the development of smarter, more connected cities. Furthermore, the integration of automated payment systems and real-time notifications contributes to improved operational efficiency and user satisfaction. Overall, the Smart Parking Management System demonstrates the potential of technology to address real-world urban problems, offering a scalable and adaptable framework for future smart city initiatives.

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Future research should focus on integrating the smart parking system with broader smart city platforms, allowing interoperability with public transport, traffic control systems, and emergency response services. Incorporating machine learning algorithms, to analyze historical and real-time data can help predict parking availability, user behavior, and peak demand periods, improving parking space utilization. Implementing a dynamic pricing model based on demand, location, and time of day can optimize revenue generation and influence parking behavior to reduce congestion.

Integrating real-time surveillance using AI-powered cameras can enhance security by detecting suspicious activities and enabling license plate recognition for access control and law enforcement. Future versions can focus on minimizing energy consumption by using solar-powered sensors, optimizing lighting based on activity, and adopting low-power communication protocols like LoRa WAN.

As electric vehicles become more common in our daily lives, the Smart Parking Management System can be enhanced to incorporate functions unique to electric vehicles, like finding charging stations, tracking the state of charging, and reserving spaces that are suitable with electric vehicles.

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