Low Cost Parking Spot Occupancy Detection Using Wireless Sensing

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***Abstract*—This paper presents a novel, low-cost approach to accurately detecting empty parking slots using wireless sensing techniques and channel state information (CSI) data. Existing solutions either rely on dedicated sensors for each parking spot, which increases deployment costs, or estimate the total number of available spaces without pinpointing their exact locations. In contrast, our approach leverages CSI-based wireless sensing to achieve accurate, real-time detection of individual empty parking slots while maintaining cost efficiency. By utilizing CSI data, our method enables robust and reliable parking slot detection even in dynamic environments. This scalable and easily deployable solution aims to improve smart parking systems, optimizing urban mobility and parking efficiency.**

***Index Terms*—wireless sensing, channel state information, parking slot detection, smart parking, parking space accounting, smart cities**

I. Introduction

The rapid urbanization and increase in vehicle ownership have intensified challenges associated with parking management. The average American spends 17 hours per year searching for parking, resulting in an estimated $73 billion in wasted time and fuel [1]. Efficient detection of empty parking slots not only alleviates traffic congestion and reduces environmental impact but also enhances driver satisfaction as well as increasing the revenue of parking facilities [2]. Traditional parking management systems have evolved from manual ticketing to sophisticated sensor-based networks. However, many parking facilities lack such systems due to their high cost and intrusive deployment requirements.

Existing solutions for parking occupancy detection often rely on deploying dedicated sensors in each parking spot, such as magnetic or ultrasonic sensors. While these methods can provide accurate occupancy information, they significantly increase deployment and maintenance costs, making large-scale implementation economically unfeasible [3]. Alternatively, some systems estimate the total number of available parking spaces without identifying the specific locations of empty slots, which limits their practicality for drivers seeking immediate parking.

Wireless sensing has emerged as a promising technology that utilizes existing wireless signals, such as Wi-Fi, to detect and interpret physical phenomena without requiring additional hardware or line-of-sight visibility. By analyzing fine-grained wireless features such as Channel State Information (CSI), wireless sensing enables applications in diverse domains. For instance, it has been used in healthcare to monitor hand movements during physical therapy exercises [4], in smart buildings to perform real-time occupancy detection for energy-efficient automation [5], and in activity recognition systems capable of classifying physical gestures and movements [6]. These studies demonstrate the versatility and robustness of wireless sensing techniques in dynamic, real-world environments. Our work builds on these principles and adapts them for the problem of detecting empty parking slots in a low-cost, non-intrusive manner.

Recent research has explored the use of wireless sensing techniques for vehicle detection as well. Most of these studies focus moving vehicles, such as those in traffic monitoring [7], rather than stationary vehicles in parking lots. There are few notable studies for parking occupancy detection as well, particularly those leveraging Wi-Fi Channel State Information (CSI). For instance, WiParkFind utilizes off-the-shelf Wi-Fi devices to monitor parking occupancy by analyzing CSI data [8]. This approach reduces the need for dedicated sensors and lowers deployment costs. However, WiParkFind focuses on estimating the number of available parking slots without pinpointing their exact locations, which can be less helpful for drivers searching for parking in real-time.

Our research addresses these gaps by proposing a low-cost, non-intrusive system that utilizes wireless sensing techniques and CSI data to accurately detect and identify individual empty parking slots. Unlike existing solutions that either require sensors for each spot or only provide aggregate occupancy counts, our approach leverages CSI-based wireless sensing to pinpoint the exact locations of vacant parking spaces. This easily accesible and deployable solution aims to improve smart parking systems, thereby optimizing urban mobility and parking efficiency.

II. Related Work

In this section, we provide an overview of related studies in the literature. There are two main approaches for parking space accounting. While some aim to detect the presence of vehicles in individual parking spots, others focus on estimating the total number of available parking spaces. In order to achieve the former, dedicated sensors are typically deployed in each parking spot, such as magnetic or ultrasonic sensors. Studies in this area have focused on improving the accuracy of these

TABLE I: Comparison of proposed parking occupancy detection solutions.

Method/References	Coverage	Low-cost?	Non-Intrusive?	Accuracy	Other Issues and Drawbacks
IR Sensors [9], [10]	Per-spot	✗	✗	High	Susceptible to weather and heat from sources other than vehicles
Ultrasonic Sensors [11]	Per-spot	✗	✗	High	Potential inaccuracies with soft or angled surfaces, as well as susceptibility to acoustic noise
Ground Wi-Fi Sensors [12]	Per-spot	✓	✗	High	Highly impractical due to the box placed on the ground at each parking spot
LoRa & RFID Sensors [13]	Per-spot	✓	✗	High	Potential for false positives, limitations in diverse environments and challenges with robustness
Vision Based [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]	Multi-spot	✓	✗	Medium	Requires high computational resources, potential privacy issues, susceptible to weather and low light
Ultra-wide-band Radar [25]	Multi-spot	✗	✓	Medium	Study does not provide experimental results for cases where multiple vehicles are present
Crowd-sourcing [26], [27], [28]	Multi-spot	✓	✓	Low	Effectiveness heavily depends on user participation
WiParkFind [8]	Multi-spot	✓	✓	Low	Only provides vacancy count rather than pinpointing individual spots
Our work	Multi-spot	✓	✓	High	

sensors, reducing their cost, or enhancing their energy efficiency. For the latter, the method is usually based on counting the number of vehicles entering and leaving the parking lot. Since this approach is less accurate than the former, as it does not provide information about the specific locations of empty parking spaces, while being much cheaper, most of the studies in this area focus on making the individual sensor technologies more cost-effective. In order to achieve this, some studies have proposed using different sensor technologies to detect the presence of vehicles in parking spaces. Others have explored the feasibility of using fewer sensors and mitigating the need for dedicated sensors for each parking spot. For this reason, we will first review the studies that focus on individual sensor technologies for parking space accounting, and then we will review the studies that focus on using fewer sensors that can be used for multiple parking spots.

A. Per-Spot Sensor Occupancy Detection

Most of the current solutions for parking occupancy detection rely on deploying dedicated sensors in each parking spot. For example, magnetic sensors are widely used to detect the presence of vehicles in parking spaces. These sensors can be embedded in the pavement and are capable of detecting changes in the magnetic field caused by the presence of a vehicle. They are relatively inexpensive and easy to install, but they may not work well in all weather conditions or with certain types of vehicles. There are also ultrasonic sensors that use sound waves to detect the presence of vehicles. These sensors can provide accurate occupancy information, but they are more expensive and require more maintenance than magnetic sensors.

Some studies have explored other sensor technologies for individual parking spaces. Some studies propose using infrared sensors to detect the presence of vehicles [9], [10]. These sensors can be used to detect the heat emitted by vehicles, making them suitable for outdoor environments. However, they may not work well in all weather conditions and can be affected by other heat sources in the vicinity.

One study has proposed using a combination of different sensor technologies [11]. This approach combines magnetic sensors with ultrasonic sensors to improve the accuracy of parking occupancy detection and increase the battery life of the sensors.

Another approach is to use wireless signals to detect the occupancy of parking spots. For example, a study has proposed using Wi-Fi signals to detect the presence of vehicles in parking spaces [12]. The sensor used in the study can provide accurate occupancy information and is relatively inexpensive. However, this approach requires a box to be installed on the ground of each parking spot, which can be intrusive and costly. There are studies that also focus on other wireless technologies, such as LoRa and RFID [13], still requiring dedicated sensors for each parking spot.

B. Multi-Spot Occupancy Detection

With the improvements in artificial intelligence and machine learning, some studies have proposed using vision-based systems for parking occupancy detection. These systems can cover multiple parking spots [2], process the images captured by the cameras, and detect the presence of vehicles in individual parking spaces. Most of these studies rely on deep learning algorithms to analyze the images and detect the presence of vehicles [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], while others use traditional computer vision techniques [24]. In addition to the high cost and computational requirements of these systems, they also have some environmental limitations. For example, they may not work well in low-light conditions or in different weather conditions if the parking lot is not covered.

One study experimentally evaluated the performance of a ulta wide-band (UWB) radar system for parking occupancy detection [25]. The study found that the UWB radar system can accurately detect the presence of vehicles in parking spaces. However, it failed to provide results for cases where multiple vehicles are present.

There have also been studies for parking spot accounting that do not require a phsical detection of vehicles. Rather, they rely on crowd-sourced data to estimate the number of available parking spaces [26], [27], [28]. These proposed solutions heavily rely on user participation and thus tend to be less accurate than the other methods.

The closest work to our study is WiParkFind, which was briefly introduced earlier. This system uses off-the-shelf Wi-Fi devices to monitor parking occupancy by analyzing channel state information (CSI) data using machine learning [8]. They used Intel 5300 Wi-Fi cards connected to two laptops to collect CSI data. The experiments were conducted in a parking lot with 10 spots. The researchers were able to predict the number of available parking slots with an accuracy of 78.2%. However, WiParkFind focuses on estimating the total number of available parking slots without pinpointing their exact locations, which our study aims to address.

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