7-2011

A Reservation-based Smart Parking System

Hongwei Wang

University of Nebraska-Lincoln, zorrowanghw@gmail.com

A RESERVATION-BASED SMART PARKING SYSTEM

by

Hongwei Wang

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfilment of Requirements

For the Degree of Master of Science

Major: Computer Science

Under the Supervision of Lisong Xu and Wenbo He

Lincoln, Nebraska

July, 2011

A RESERVATION-BASED SMART PARKING SYSTEM

Hongwei Wang, M. S.

University of Nebraska, 2011

Adviser: Lisong Xu and Wenbo He

In metropolitan areas, parking management influences drivers search time and cost for parking spaces, parking revenue, and traffic congestion. The wide deployment of wireless parking meters with sensing and communications capabilities allows the parking authority to monitor the state of each parking space in real time and optimize the parking management.

In this thesis, we study state-of-the-art parking policies in smart parking systems, and show that the smart parking system needs to be "smarter". Our design goals of the smart parking systems include: (1) simplify the operations of parking systems, (2) improve drivers' satisfaction, (3) increase parking revenue, and (4) alleviate traffic congestion. Through analysis and simulations, we first show that the proposed reservation-based parking policy has the potential to achieve the above goals. We then model the behavior of both service providers and drivers in smart parking systems, and explore the dynamic pricing scheme to achieve the goals in smart parking system design.

Furthermore, we design and implement a prototype of Reservation-based Smart Parking System (RSPS) that allows drivers to effectively find and reserve the vacant parking spaces. With the real time tracking of parking status via various sensing technologies, a smart parking system will dynamically update the parking price according to the physical parking status, and the parking price will affect drivers decision on parking slot selection, therefore, affect the parking status. A smart parking system can be regarded as a full-fledged cyber-physical system (CPS).

Through extensive experiment based on real traffic traces and a real-world parking map, the results show that the proposed reservation-based parking policy has the potential to simplify the operations of parking systems, as well as alleviate traffic congestion caused by searching for parking.

ACKNOWLEDGMENTS

I am heartily thankful to my supervisor Dr. Wenbo He for accepting me as her student and for providing me the opportunity to work on the cutting-edge project of Cyber-Physical Systems. I would also like to thank her for her encouragement, guidance and unfailing support throughout the completion of my research project and this thesis.

I owe my deepest gratitude to my co-supervisor Dr. Lisong Xu for taking time out of his busy schedule and providing his valuable expertise and guiding me through the completion of this thesis. I would also like to thank Dr. Byrav Ramamurthy for agreeing to be on my committee and for providing valuable feedback and comments on my thesis.

I am grateful for my dearest friend Fan Zhang for his motivation and encouragement in a number of ways. I would also like to thank Landu Jiang for always being there for me

I would like to thank my parents for always being supportive of me and believing that I could get through this.

Lastly, I offer my regards and blessings to all of those who supported me in any respect during the completion of this project.

Contents

List of Figures

Chapter 1

Introduction

The study of Cyber-Physical System (CPS) has become a key area of research. It refers to a new generation of systems with integrated computation and communication capabilities that allow users to interact with the physical world. The ability of interaction with physical world is a key catalyst for future technology development. CPS, therefore, provides significant opportunities for design and development of next-generation traffic management solutions. As an important component of traffic system, parking management system is playing an important role and affecting people's daily life. By detecting and processing the information from parking lots, smart parking system allows drivers to obtain real-time parking information and alleviates parking contentions, which is a practical application of CPS.

The parking industry generates billions of dollars in annual revenue in the United States alone, and parking regulations may affect people's concerns about traffic congestion, air pollution, drivers' frustration about parking searching, and municipal objectives. For instance, a recent survey [29] shows that during rush hour in most big cities, the traffic generated by cars searching for parking spaces takes up to 40% of the total traffic. Therefore, in these densely populated urban areas, a certain amount of traffic congestion and delay are due to parking. A recent study [25] shows, in a business district of Los Angeles, vehicles looking for parking burn 47,000 gallons of gasoline and produced 730 tons of carbon dioxide, which is equivalent of 38 trips around the world. Clearly, the problems associated with parking imposes significant societal costs, both economically and ecologically [18].

In order to address these problems associated with parking, smart parking systems aiming to satisfy the involved parties (e.g., parking service providers and drivers) have been developed. However, most current smart parking or parking guidance systems [1, 2] only collect and publish live parking information to direct drivers to available parking spaces near their destinations. These systems are not "smart" enough, because they cannot successfully help drivers find a desired parking space in crowded areas, and sometimes make the situation worse. For example, if available spaces in a congested area are less than the spaces in demand, more drivers trying to park will head for the limited available spaces, causing severer congestion. In this case, detailed information associated with parking availability would allow drivers to make better decisions on use of parking lots and road-side parking.

In contrast to such parking information guidance systems, this thesis presents a *Reservation-based Smart Parking System* (RSPS) that not only to broadcast real-time parking price based on the parking availability to the drivers as part of a communal application, but also to provide reservation service as part of user-targeted service. Built on advanced sensing and mobile communication techniques, RSPS processes streams of timestamped sensing data from sensor network in parking lot, calculates the real-time parking price based on parking availability information and publishes the parking price to the drivers. On the other side, the drivers can retrieve parking price and reserve their desired vacant spaces via Wi-Fi or Internet.

1.1 Approach

As the technical foundation of smart parking system, computing devices (e.g., smart phones, wireless sensors and personal laptops) turn progressively smaller, cheaper and more powerful. As a result, mobile and pervasive computing is becoming an indispensable component in the distributed networked computing infrastructures. It provides us a powerful platform to compute real-time information from physical world (physical part), as well as communicate with people (cyber part). Cyber-physical systems are so involved in the everyday life that we should not underestimate their impacts. In this thesis, the objective of smart parking system is to develop technologies which will help to build a mobile and real-time computing system which make the computing and communication capabilities fully play, and elegantly integrated with users.

1.1.1 A Reservation-based Solution

Based on the observation that parking space reservation can help drivers to reduce the search time dramatically, we propose a reservation-based solution, built on advanced sensing and mobile communication technology, with the objectives to alleviate the parking contention, balance the benefits between parking service providers and drivers, coordinate among service providers, differentiate the needs of individual drivers, and reduce the amount of traffic searching for parking as well. To achieve the design goals, a powerful tool to model the behavior of both service providers and drivers is required. Meanwhile, we need to design control signals to guide the parking selection of large scale, autonomous drivers.

1.1.2 Dynamic Pricing Scheme

Normally, a parking system manages the parking resources, and the drivers buy or reserve the permits to park somewhere they want within a specific parking district for the chunk of time they purchase. In the proposed model, the parking management system adopts dynamic pricing scheme to generate prices for parking spaces in different parking lots. The parking price reflects the real time parking availability. It not only serves as a control signal to balance the parking lot utilization, but also improves the revenue for service providers. On the other hand, drivers rely on the utility functions to determine where to park (e.g., select the most convenient parking spaces) under a certain budget constraint. Through the simulations, we will show that: the amount of traffic searching for parking is reduced, the solution guarantees the service quality for different users and the revenue is increased for service providers.

1.2 Contributions

In this thesis, we propose a reservation-base smart parking management solution. It implements a dynamic parking price scheme and reservation parking service. Moreover, we design and implement the prototype of a Reservation-based Smart Parking System (RSPS) to evaluate the proposed reservation-base smart parking management solution. We summarize the contributions made by this work as follows.

- The RSPS provides parking reservation service, which focuses on the entire parking condition in certain area, instead of single parking lot. With the real-time reservation service, the drivers can find and reserve their desired vacant parking spaces quickly. Therefore, the gasoline and time in search of vacant parking space is reduced.

- We design the dynamic parking price scheme for parking service. In order to satisfy the different concerns from different parts in parking system, the dynamic price scheme is designed to generate more parking revenue, provide differentiated services for different drivers and reduce the parking congestion. In this thesis, we demonstrate that it is able to reduce the traffic congestion caused by parking searching.

- We demonstrate the usefulness and effectiveness of RSPS by implementing a prototype. In this project, we design and develop the three-tier architecture, (1) data tier: deployed sensor network to collect real-time parking information, (2) logic tier: dynamic pricing engineer in process of sensing data, (3) representation tier: web service.

1.3 Thesis Organization

The rest of this thesis is organized as follows. In Chapter 2, we set the background of the proposed research by introducing performance metrics and several existing approaches for smart parking systems, and summarize the related work. In Chapter 3, we present the details of Reservation-based Smart Parking (RSP) management solution. In Chapter 4, we present the detailed architecture of proposed reservation-based smart parking system. In Chapter 5, we evaluate the proposed RSP management solution through extensive simulation. Finally, we conclude this thesis and discuss the future work in Chapter 6.

Chapter 2

Background and Related Work

In this thesis, we mainly focus on a management system that assists drivers to find parking spaces in a specific parking district, and satisfies the needs of both parking providers and drivers. In addition, an important goal of the system is to reduce the traffic searching for parking, hence reduce energy consumption and air pollution. In this chapter, we review background on smart parking systems, including the performance metrics, existing solutions and challenges. We also briefly discuss the related work.

2.1 Performance Metrics

To evaluate the performance of a parking management system, we introduce the following metrics, which reflect the needs of involved parties, and our concerns on traffic congestion and environmental protection.

- *Walking Distance*: Walking distance is defined as the distance from a driver's selected parking space to the destination. It is an important factor for a driver to determine where to park. Usually, a driver wants to park as close to the destination as possible if his budget permits. Therefore, the walking distance indicates the satisfaction of drivers.

- *Parking Revenue*: Regardless of whether a parking lot is privately owned or municipally owned, parking revenue represents the benefit to the parking providers. Since multiple parties are involved in this system, our design does not aim to maximize the parking revenue for service providers only, but allows them to obtain profits at reasonable level.

- *Service Differentiation*: Usually a driver wishes to pay as little as possible, and has a certain budget for parking. In a crowded area, the parking resource is limited. To alleviate the contention on parking resource and maintain reasonable parking revenue for service providers, the management system should differentiate the drivers according to their budget and need.

- *Traffic Searching for Parking*: The traffic generated by drivers searching for parking is not negligible and reflects the social welfare. Hence, an efficient parking guidance system should efficiently reduce the traffic searching for parking. Also, reducing the amount of searching time for parking is desired by drivers.

We investigate performance of the proposed smart parking system using these performance metrics.

2.2 State-of-the-art Parking Management Solutions

We now introduce several existing parking guidance approaches and show their limitations. We simulate the parking system performance under different parking management strategies and show results in Chapter 5.

- *Blind Search*: Blind searching is adopted by users when no parking information is available. So drivers search parking spaces randomly within a certain distance to their destination. If a driver gets an available space, the driver will stop searching; otherwise, the driver will continuously searching in the neighboring parking lots until he finds space. In this case, there is no control signal to guide drivers' behavior.

- *Parking Information Sharing (PIS)*: This mechanism represents the current state of the smart parking system design. When a driver obtains the parking availability information near his or her destination, the driver will know if the desired parking lot has available spaces. Hence, individual drivers make the decision according to the parking availability information. If a parking lot has a very few parking spaces available in busy hours, it is likely that more drivers struggle for less parking spaces. This phenomenon is called "multiple-car-chasing-single-space", which may cause severe congestion.

- *Buffed PIS (BPIS)* To alleviate the "multiple-car-chase-single-slot" phenomenon, some designers of smart parking systems have devised a solution to leave a buffer when publishing the live availability information. Therefore, if a parking lot has less unoccupied spaces than a threshold, the system will show that the parking lot is fully occupied. But it is difficult to determine the threshold for the buffer. If the buffer is too small, the problem of "multiple-car-chase-single-space" will not be eliminated. If it is too large, the utilization of parking spaces will be low.

2.3 Challenges

Given the design objectives of smart parking systems that requires the coordination among multiple parties, we summarize the main design considerations as follows:

- *Performance v.s. Overhead*: In order to complete parking space reservation, drivers have to communicate with the system. However, there is a tradeoff between the overhead to generate and convey control signals to drivers v.s. performance optimality. For example, if the system computes the fine-grained control signals for individual drivers and adopts unicast to inform the drivers about parking system status and instructions, the overhead will be very large. Hence, the parking management system generates a uniform control signal (e.g., the utilization of parking lot and parking price), and broadcasts the control signal to drivers.

- *Trade-off Between Benefits to Drivers and Service Providers*: Multiple parties (drivers and service providers) are involved in the parking system operation. The state of the system depends on their interaction with each other. To balance the needs of involved parties, we use parking price as the control signal to coordinate the involved parties.

- *Differentiated Service for Large Scale Autonomous Drivers*: Thousands of drivers make parking decision autonomously. They have different needs and budgets for parking and their interpretation of parking information is different. Providing differentiated service for drivers is important to satisfy individual users. In this sense, the service quality is determined by parking price.

As alluded to above, the blind search system is an open loop system, where users make decision without looking at the state of the system. The PIS and

BPIS strategies allow drivers to make decisions based on the system state (e.g., parking availability information). However, since the drivers can obtain the information of parking availability, they may pursue limited parking spaces in busy district resulting more traffic contention. To solve this phenomena of multiple-car-chase-single-space and reduce the traffic searching for parking, we suggest a reservation-based system, where drivers make reservations through the parking management system. If a driver makes the reservation successfully, it guarantees an available parking space for him, and the driver can park at the reserved space without searching. The reservation-based system allows drivers to select the most convenient parking space under their budget constraints. To address the design challenges, we use a dynamic pricing scheme to determine the reservation charge for parking. This will regulate the parking behavior of drivers, and fulfill the needs of service providers. The detailed model for drivers and service providers is introduced in Chapter 3.

2.4 Related Work

Currently, most research work on smart parking is from the perspective of system design, which focus on implementing a wireless sensor network to detect parking information and provide real-time parking service. In addition, we introduce the pricing-related topics in networks, which provide us a powerful tool to manage parking lots.

2.4.1 Cyber-Physical System (CPS)

As the frontier of current research, CPS is revealing numerous opportunities and challenges, and encouraging multidisciplinary collaborative research between academia and industry [30]. Although it is difficult to make a clear definition of CPS, it is consider as a physical and engineered system integrated with monitored, coordinated and controlled operations, as well as a computing and communication core[21]. From the nano-level to the world-scale systems, the cyber-world of computing and communications with the physical world is transforming the way that how humans interact with and control the physical world around us.

The innovative applications, such as [12], in CPS have great social and economical impact for national competitiveness. Many researchers focus different areas of CPS, including transportation system [23], biomedical and healthcare systems[13], defense and aerospace industry, and smart grid and renewable energy [6]. As the major energy consumer, the revolution of transportation holds great promise. According a recent survey in 2010[4], the transportation consumption of total energy in U.S. reached 29.2% in 2008, which is the highest record since 1973. And 88% of these trips are by car in U.S. [3]. As a result, daily commuting represents a significant part of total transportation consumption. The research on transportation of CPS focuses on the smart transportation systems, which is aiming to reduce energy consumption, and driverless systems. In [15], the author investigates the optimal transportation emission reduction strategies and identifies optimal ways to reduce transport energy consumption and pollution emissions. Furthermore, the DARPA Grand Challenge [12], which is a competition for driverless vehicles, is an important application of CPS. The researchers from different institutions design and develop a variety of different software and hardware combinations for interpreting sensor data, planning, and execution.

Since CPS can be considered as a confluence of distributed embedded systems and real-time system [21] interacting with physical world, the precision of computing and communication is interfaced with the uncertainty and noise in the physical environment. There are several research challenges for CPS, including (1) CPS composition, (2) robustness, safety, and security of CPS, (3) control and hybrid systems, (4) computational abstractions, (5) architecture, (6) real-time embedded systems abstractions, (7) sensor and mobile networks, (8) model-based development of CPS, (9) verification, validation, and certification of CPS and (10) education and training.

As an important application of CPS, transportation cyber-physical system [5, 32, 31, 9] enables people to reach their destination safely and reliably. In [5], the author mainly discusses the cyber-physical aerospace, which is relevant to the challenges and future directions in transportation and exploration systems. The transportation cyber-physical system improves the dramatic safety and transportation efficiency, such as anti-lock brakes and advanced flight management systems. The air transportation network is an example of transportation cyber-physical system. The air traffic is suffering adverse weather and density problem. The CPS should provide an adaptive flight planning capability with seamless integration of strategic and tactical reasoning system. In [32], the author describes the impact of the mobile internet to change the transportation cyber-physical system. With the rapid development of mobile technology in last five years, it is constructing the dedicated infrastructure systems to monitor traffic. The Smartphone with localization module is changing the traffic monitoring system. It is able to provide the real-time traffic information for entire transportation network. As one of the first instantiation of transportation cyber-physical systems, the traffic information system is being progressively influenced by mobile technology. On the other hand, there are still some promising and fundamental challenges of mobile device technology remaining to be solved. In [31], the author presents the limitations of current automotive Cyber-Physical System. Because of its vehicle-centric view, it only provides partial information about surrounding environment. Therefore, it is not fit for satisfying the needs of embedded human in the system. The new automotive CPS should be more open and flexible to develop new human mobility models. In [9], the author discusses substantial technological and engineering advances of transportation CPS, it provides the advanced autonomous control choices for cars, trains, and aircraft. With the correct automative control, it ensures a safe operation of the control assistants under all circumstances.

Another instantiation of CPS is advanced electric power grid [19, 21], which is one of the largest complex interconnected networks. In [19], the author introduce the new power grid, power electronics, and embedded control move, based on concepts of CPS, beyond centralized monitoring to active, distributed, control of the power grid. In [21], the author presents some new challenges of developing a fully integrated robust, stable, failure-free advanced power network with interacting distributed, intelligent real-time control through the composition of cyber and physical resources. The specific aspects include multiple time scales of interacting, distributed and control, high resilience, security policy and sustainable power system.

2.4.2 Bay Area Rapid Transit

As an important application of CPS, smart parking management systems have been designed to more efficiently use parking capacity. The smart parking management field test at the BART station in the East San Francisco Bay Area is good example to demonstrate the feasibility of smart parking systems and describe the specification of its technology [24]. The authors complete a comparative evaluation of rider attributes at three BART stations to be identified as the potential sites. The data from drivers at three stations provide the insight of potential demand for smart parking system. Since the drivers also appear to use the Internet frequently, it demonstrates the potential of smart parking reservation service, which will be detailedly discussed in Chapter 3. In order to evaluate the smart parking field, they implement two user interfaces: two VMSs that display parking availability information, and a centralized intelligent reservation system. The survey results from their test suggest that a potential market for a daily paid parking service. However, only providing availability information may cause some other serious problems, such as the "multiple-car-chase-single-slot" phenomenon.

2.4.3 Parking Lot Detection

As a part of Smart Parking System, the parking lot detection has been developed by Jake Reisdorff *et al.* [22] as a course project under the supervision of Dr. Sharad Seth in Computer Science & Engineering at University of Nebraska-Lincoln. The project is aimed to providing a parking garage detection solution that is accessible by a webpage. Specifically, they focus on the Stadium Drive parking garage on the UNL city campus on which to test their project. They use a mounted camera in the garage to take images from a static position, and send to a web server. The server runs an image processing application to detect if the parking spaces are available or not, and deliver the raw data of image process to the web application. Based on the raw data, the web application determines the number of unoccupied spaces, and show a map of parking garage with availability information.

2.4.4 VANET-Based Smart Parking

With development of Vehicular Ad-Hoc Network (VANET), VANET-Based provides another option for smart parking systems. In [8], the authors present a smart parking management system based on wireless sensor network technology, which provides remote parking monitoring, automated guidance and parking reservation service. They demonstrate this system architecture can help commuters to find vacant parking spaces. Rongxing Lu *et al.* [16] introduce a new Smart PARKing (SPARK) scheme, which is based on Vehicle Ad Hoc Networks (VANET), provides drivers with accurate and convenient parking services in large parking lots, including real-time parking navigation, intelligent antitheft protection, and friendly parking information dissemination. In [7], authors proposed a scalable information dissemination algorithm for discovery of free parking spaces via VANET.

2.4.5 Resource Allocation

Furthermore, appropriate parking control to motivate drivers to balance their parking demands is another goal for smart parking system. Pricing policy, as an important economic tool, is effective to allocate resource in network. In [11], Kelly *et al.* show that, when selfish users seek to maximize their benefits, the system can provide incentives to reach the optimization of global network. In [28], authors proposed a reasonably complete DiffServ pricing model integrated a pricing structure for different service class and the demand behavior of users. They show that, when different service classes operate at different target utilization, they provide different levels of service, and users see a stable service price and maintain stable. Moreover, Feldman *et al* in [10] formulate the fixed budget resource allocation game and study the existence and performance of a distributed market-based resource allocation system.

Chapter 3

Reservation-based Smart Parking Management Solution

In this chapter, we present the proposed Reservation-based Smart Parking (RSP) management solution, which implements a reservation policy and dynamic pricing scheme.

3.1 System Architecture

Fig. 3.1 shows three components in the system, including parking lots, users and the management system. The management system determines the dynamic parking prices based on real-time parking information, and broadcast live parking prices to users (also drivers). The price reflects the relationship between demand and supply, and implies the congestion level. Upon receiving dynamic parking prices, the user selects a desired parking lot and reserves a space in the parking lot. According to his budget constraint and convenience degree, the parking decision would vary by user. As a result, the state of parking resources is changed by users'

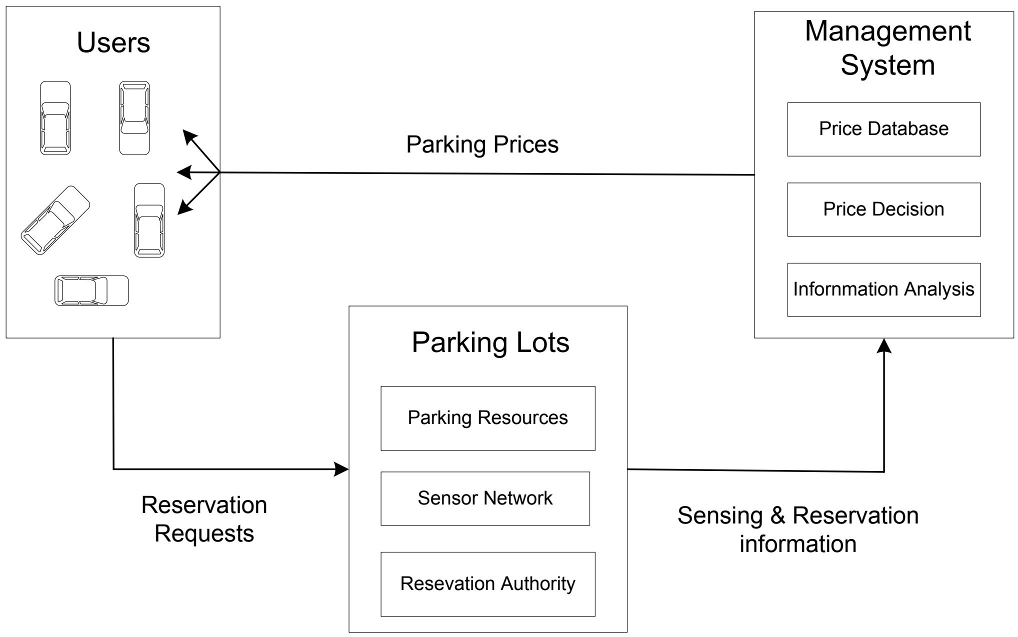

Figure 3.1: Integrated Smart Parking Management System

parking decisions. The parking lot consists of a group of parking spaces. The on-street parking can also be considered as a virtual parking lot. The state of a parking lot is the number of occupied spaces versus total spaces. Every parking lot has access to the Internet to communicate with the management system and users, and share parking information with other parking lots. In each parking lot, the reservation authority is deployed for authenticating the individual user's identity and reservation request. In this case, the reservation authority in the parking lot communicates with the specific user individually. Once the reservation order is confirmed, the reservation authority updates reservation information to hold the related space for the user. The sensor system deployed in parking lot is responsible for monitoring the real-time condition of parking lots and delivers the live aggregated sensing information (the number of available spaces or occupancy rate) to the management system. The sensing information is updated on demand.

Upon retrieving the parking information, the management system updates the state of the parking lot. Based on the state of parking lots, the management system (1) analyzes their occupancy status and congestion level, (2) determines the parking prices according to dynamic pricing scheme, (3) broadcasts the prices to all users periodically, and (4) stores the parking information and prices for further analysis. The management system serves as the centralized decision-making body in a planned economy. It makes all pricing decisions regarding the state of parking lots and user demands [20]. This system is a closed-loop system to dynamically adjust parking price, balance the benefits between users, and service providers and reduce traffic searching for parking.

By placing the reservation authority in individual parking lots, we simplify a lot of issues related to the implementation, including communication overhead, reservation synchronization and load balancing. Since each user only has to communicate with his desired parking lot to make his reservation, rather than the centralized management system, the communication overhead of reservation is highly reduced. Also, since each parking lot manages its own reservation information, it makes the reservation requests from users easily to be synchronized, comparing with reservation synchronization in the management system.

3.2 Model of User Behavior

To model user behavior, we use the framework of the competitive market model [27], which includes two agents: consumers and producers. To describe the relationship between service providers (also producers) and users (also consumers), the price of parking service is defined as the exchange rate of parking spaces, dynamically determined by parking demands and congestion level. Given dynamic parking price, a user selects a parking space under his budget constraint. Upon receiving the prices of parking lots that have available spaces, the user selects a convenient lot to park from those whose prices are acceptable. In order to model the parking decision behavior, we define the *utility function* to balance the convenience and cost in the parking process.

In the real world, users desire to maximize the convenience and minimize the parking cost, though trade-off must be made. Here, given the parking price p of specific parking lot, the *relative cost* is defined as a function of p, $C(p) = \kappa p/b$, where κ denotes the user's sensitivity to the price and b is the budget constraint of the user. In this case, a user with higher budget will have more tolerance for higher price and tend to pursue the parking space providing more convenience. Meanwhile, the convenience can be measured by walking distance d, hence the gain of a user is a function of d,

$$B(d) = v \log \frac{d_m}{d}, \quad \text{for } d \leq d_m \tag{3.1}$$

where B represents the convenience if the user selects a parking lot with the walking distance d, d_m denotes the maximum walking distance the user can tolerate, and v represents the sensitivity to walking distance. As represented in the literature [11][28], when all user utilities are defined as logarithmic, the optimal solution becomes proportionally fair. Accordingly, the optimization of the utility function for a user's task of parking selection in an area that contains multiple parking lots, is represented as

$$\begin{aligned} \max_j U &= \max_j \left[B\left(d^j\right) - C\left(p^j\right) \right] \\ &= \max_j \left[v \log \frac{d_m}{d^j} - \kappa \frac{p^j}{b} \right] \\ \text{s.t.} \quad & p^j \le b \quad d^j \le d_m \end{aligned} \tag{3.2}$$

where p_j represents the parking price at j_{th} parking lot and d_j is the distance from j_{th} parking lot to the user's destination. Note that, since users make their parking decision during one time slot, the utility function is only for a given time slot.
For an individual user, the parking decision is to maximize the utility, which is a function of parking price and walking distance. The user's decision cannot have impact on other user's decision, although the parking price may be modified by the change in demand of the users. Furthermore, in reality, a user with high budget may desire more convenience, which means the maximum walking distance he can tolerate may be less. In our model, to avoid computation complexity, we use the constant values for maximum walking distance and budget to imply this relationship.

3.3 Dynamic Pricing Scheme

Service providers that own the parking resources (parking lots) collect real-time parking information to determine the parking prices, and broadcast them to the drivers to help them make reservations. From the perspective of service providers, dynamic pricing scheme is for generating more revenue from the parking service, supporting service differentiation for users with different requirements and budgets, and reducing the traffic searching for parking. On the other hand, users desire to learn parking information from the parking price and obtain the guarantee of service quality.

In order to achieve these design goals, the formulation of dynamic pricing is decomposed into *usage price* (p_u), *statistical price* (p_s), and *congestion price* (p_c). Specifically, the *usage price* is determined by the real-time state of parking lot aiming for reflecting real-time parking condition and increasing the revenue; the *statistical price* is measured by the historical price, which provides users with a reasonable price for their reservation time period and reduce the potential traffic of parking searching; and the *congestion price* reflects the congestion in near future, and prevents the sudden increase of the parking demand. Both *usage price* and *congestion price* are computed periodically, with the interval τ, *statistical price* is computed on demand. The parking price p is represented as

$$p = \beta_u p_u + \beta_s p_s + \beta_c p_c \tag{3.3}$$

where β_u, β_s, β_c represent the different weights for different price components. Note that the combined parking price p is the average price for total reservation time.

3.3.1 Usage Price

The usage price is determined by resources consumed, specifically the occupied parking spaces, and users' potential demands. The usage price (p_u) is set such that it can maximize the revenue, corresponding to various costs of service provider associated with real-time state of resource. Given an individual parking lot with J parking spaces, the usage price during i_{th} time slots is p_u^i, which is limited by number of users demanding parking. The pricing decision is to obtain the optimal profit:

$$\max_{p_u^i} \left[\sum_i^I (x^i p_u^i - f(j^i, J)) \right] \tag{3.4}$$
$$\text{subject to: } x^i, j^i \le J$$

where x^i represents the total demand for parking spaces with price p_u^i during i_{th} time slots, I is the total time slots, and $f(j^i, J)$ is the function of parking cost associated with occupied parking spaces j^i and total parking spaces J.

According to the utility function of users described above, users select their parking lots based on walking distance and parking price. However, since users estimate walking distance depending on their own capability and other unexpected factors, the service provider cannot learn this behavior from the users. So we simply assume that the total demand x^i for parking spaces with price p_u^i is determined by the price, which can be represented as

$$x^i = \frac{C^i}{\delta^i p_u^i} \tag{3.5}$$

where C^i represents the total number of users whose budgets are higher than p_u^i and δ^i is the parameter of preference to choose a parking lot with price p_u^i.

Denote the basic price of parking service with the lowest utilization by p_{basic}. φ^i is used for adjusting the basic price based on real-time state of parking lot, the service price can be estimated as $p_u^i = \varphi^i p_{basic} / (1 - \sigma^i)$, where σ^i is the utilization of specific parking lot. The effective demand associated with σ^i is $C^i / \delta^i p_u^i (1 - \sigma^i)$.

Accordingly, the Equation (3.4) can be written as

$$\max_{p_u^i} \left[\sum_i^I \left(\frac{C^i}{\delta^i p_u^i} p_u^i - f\left(j^i, J\right) \right) \right], p_u^i = \frac{\varphi^i p_{basic}}{(1 - \sigma^i)} \tag{3.6}$$
$$\text{s.t. } \frac{C^i}{\delta^i p_u^i (1 - \sigma^i)} \le J, \quad \varphi^i \le 1$$

The optimal problem of the Lagrangian is represented as

$$\max_{p_u^i} \left[\sum_i^I \left(\frac{C^i}{\delta^i} + \lambda \left(J - \frac{C^i}{\delta^i \varphi^i p_{basic}} \right) - f\left(j^i, J \right) \right) \right] \tag{3.7}$$

The optimal solution is

$$p_u^i = \frac{C^i}{\delta^i J \left(1 - \sigma^i\right)} \tag{3.8}$$

3.3.2 Statistical Price

The statistical price is set to predict the parking price beyond the current time slot. If a user reserves a parking space during the upcoming time slots, the service provider will impose an opportunity cost by depriving other users of the opportunity to be admitted to use that parking space. However, the live usage pricing cannot correctly reflect the opportunity cost in the future. In this case, the service provider has to provide a new fair charge to predict future parking price, instead of selling resources at the current usage price. Since the total traffic flows are periodic, the parking conditions are similarly changing. Therefore, the historic data provides the service provider a powerful tool to predict the parking price over future time slots. So the statistical price (p_s^i) of parking reservation service is defined as

$$p_s^i = \frac{\sum_i^{I'} \left[\varrho p_u^{i_{avg}} + (1 - \varrho) p_u^{i_{(k-1)}} \right]}{I'} \tag{3.9}$$

where p_s^i is the statistical price for the i^{th} time slot during the current time period k^{th} (we use one day works as one time period that consists of I time slots), I' is the total time slot that user reserves, $p_u^{i_{avg}}$ is the average usage price at the i^{th} time slot in all last periods, $p_u^{i_{(k-1)}}$ is the usage price at i^{th} time slot during last $(k-1)^{th}$ time period, and ϱ is weight parameter.

By providing users this statistical price, the service provider lets users learn the future parking price, which can prevent potential congestion. At the same time, since the statistical price can predict the future usage price, this more reasonable price allows the service providers to increase the revenue and users' satisfaction.

3.3.3 Congestion Price

To avoid many users pursuing a few parking spaces and alleviate traffic congestion caused by parking searching, we propose an additional price component, which is congestion-sensitive to encourage users to balance their parking selections and reduce congestion. The congestions considered are traffic congestion and parking congestion. Since the traffic congestion cannot be monitored by parking sensors directly, and many traffic congestions are not caused by parking searching, we only focus on the growth rate of parking occupancy to indicate traffic condition. If the traffic searching for parking spaces gives contribution to traffic congestion, the rate of parking occupancy has to grow dramatically in short time. Moreover, when the available parking spaces are lower than a certain proportion, it will cause parking congestion and conflicts if too many users pursue these spaces. Therefore, two kinds of congestion pricing are considered: pricing when the growth rate of occupancy exceeds a certain threshold, and pricing when the parking occupancy reaches certain level. Both pricing are calculated iteratively to prevent the price highly oscillating. This kind of change in price, increasing when the supply is below users' demand and decreasing when the supply exceeds users' demand, can regulate the relationship of supply and demand to reach certain equilibrium.

In this paper, we classify the congestion level with congestion factor l. When the congestion factor exceeds the threshold of certain level, an additional congestion price is charged. The congestion price p_c^i during i_{th} time slot is given by

$$p_c^i = \left\{ p_c^{(i-1)} + \xi^l \frac{dr}{di} + \omega^l \frac{\left(r^i - r_{avg}^i\right)}{r_{avg}^i}, 0 \right\}^+ \tag{3.10}$$

where ξ^l and ω^l are the congestion parameters to adjust the weight according the different congestion factors l, and r^i and r_{avg}^i represent the occupancy rate and average occupancy rate during i_{th} time slot.

During the congestion, the users have to suffer the extra congestion charge, or select other parking lots with lower parking charge. So Equation (3.10) drives the user demand towards the parking lots with lower occupancy rate and less growth rate. The provider applies the congestion charge when the congestion reaches certain level, and adjusts the congestion charge and level dynamically according to the real-time parking information. After the congestion is removed, the congestion price is decreased gradually to zero to avoid further congestion and price oscillation if new congestion is found.

In this section, we have presented a dynamic pricing scheme consisting of three different pricing components: *usage charge*, *statistical charge* and *congestion charge*. Both the usage price and congestion price are adjusted periodically in a given time scale. And the real-time price information is stored in a database for statistical price and further analysis. In reality, the users only need to know the total price, instead of specific price components.

Chapter 4

System Design

With the model details as given above, we now present the design of Reservation-based Smart Parking System (RSPS). The various components of our design are closely inter-related. Given this interaction, we first present the design concerns of the system in this section, before moving on to the details in subsequent sections.

- *Reservation Performance*: The RSPS utilizes both the Internet and Wi-Fi, whereby drivers can check the real-time parking information and complete their reservation. However, there is a bottleneck to the system when many drivers are simultaneously making reservation. In this case, the system has to synchronize the parking information and handle each reservation request, which significantly reduce the system performance, and even cause some conflicts. In order to address this challenge, we design a distributed reservation strategy implemented in the proposed smart parking system. When a driver selects the desired parking lot, the system will reconnect the driver to the subsystem in related parking lot, the driver can complete the reservation without communicating with the central system. Therefore, the central system no longer needs to maintain the reservation service.

- *Data Collection and Local Presentation*: The system collects and stores the data about the performance metrics, including the status of parking space, reservation time, parking location, driver's identity. All data stored by the system is at least stamped with time metadata. Furthermore, the system allows the driver to check the parking information, including the location of parking spaces, the vacancy time of parking spaces and reservation information. In order to protect the security of the system, we separately design a repository of sensing data and a mirror database of reservation. The repository is the sink of the sensing data, and the mirror database is synchronized with the repository and stores the reservation information. In this way, the drivers are only able to check and update the information in the mirror database.

- *Drivers' Identity Verification*: Once the reserved space is detected to be occupied by a vehicle, the system should verify the driver's identity. If he/she did not reserve the space, the system will alarm the driver this space is reserved. In our proposed system, the drivers can visit the website and verify their identity via Internet. If they cannot access Internet, the drivers are able to communicate with the sensors by Bluetooth wireless connection.

4.1 Hardware Design

The system hardware is organized into three main components, the sensor network, the central server and the mobile device, as shown in Fig 4.1. In the following, we discuss the detailed design and implementation of each component, along with the specification of communication between them. In our project, we developed a number of functions on Zigbee sensors that provide a continuous measure of parking status for each space. Each sensor is integrated with two wireless mote.

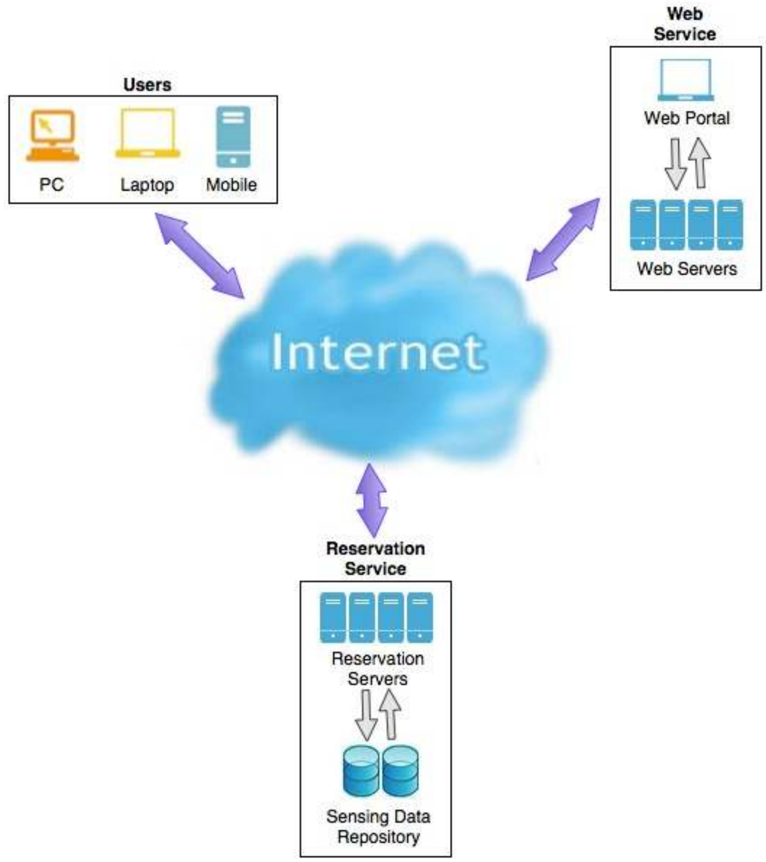

Figure 4.1: Data Communication among Components

The wireless mote platform provides a 250 kpps 802.15.4 wireless radio, 8 channel A/D and an 8 MHz microcontroller for on board digital signal processing. Mote 1 hosts light and vibration sensors, which is used to detect the vehicles. In reality, the light sensor is easily interfered by light sources. So we use highly directional beam to strengthen light and reduce the interference. Mote 2 hosts the communication module of Bluetooth. As a result, the sensor bridges the communication between the Zigbee on mote and the Bluetooth module on smartphone (e.g., Android G1). In this case, the sensor confirm the identity of users when vehicle is detected in reserved parking lot.

The mobile phone is used to assess Internet, over Wi-Fi or a GSM cellular network, to obtain the information of parking availability and make parking reservation from the Internet server. The mobile phone also provides the Bluetooth module to communicate with sensors when verifying the driver's identity.

There are a central Ethernet-connected server deployed with storage and computational power. These servers provide hardware support for the software services, which are described in section III.C. In particular, it is for system users to request the services of parking information and parking reservation. Once user's reservation is authorized, the server will update the state of related parking sensor by wireless low power link, IEEE 802.15.4.

4.2 Software Design

Fig. 4.2 shows the design of software architecture, primarily defining the *iRev*, which is the central location of the system to host applications and functions as the point of control and configuration for the distributed system. Primary software elements are discussed in the following.

RSPS has a subsystem of sensor network in the parking lots. The sensor networks provide the real-time parking information to the upper layer. Here we categorize sensor nodes to detecting nodes and collecting nodes. Specifically, the detecting nodes take the responsibility to monitor the status of parking spaces, as well as communicate with mobile phones. Moreover, the collecting nodes advertise itself as the root node and are responsible to collect and deliver the detected event and data from detecting nodes.The sensor nodes are able to achieve end-to-end connectivity across a set of nodes and access points by implementing collection tree protocol.

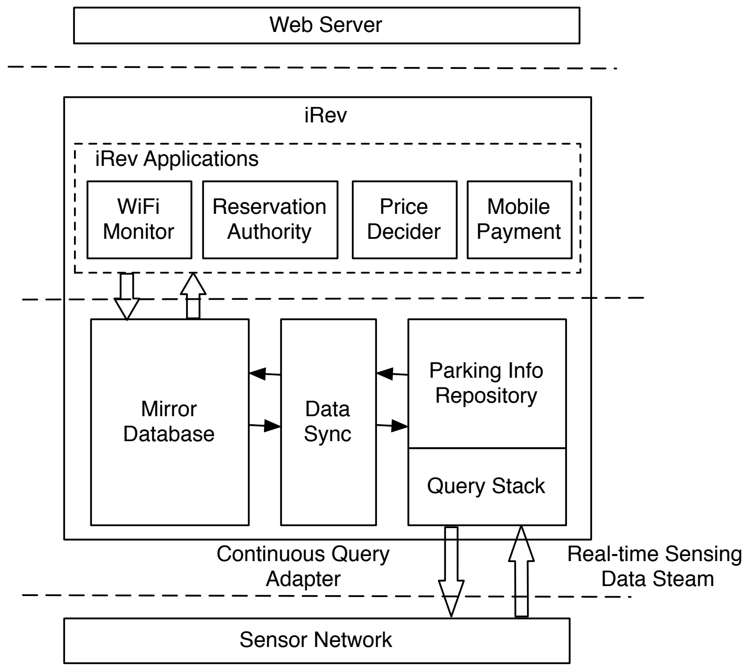

Figure 4.2: Architecture of Parking Management System

As the middle layer between the sensor network and web server, the iRev is the sink for all data sent from the lower sensor nodes. To simplify application development, we have developed query stack for delay-tolerant continuous query processing. Meanwhile, the parking information repository can retrieve real-time sensing data stream. To transfer data efficiently and reduce the complexity of the system, we have developed data synchronization processor that can connect and synchronize the data between parking information repository and mirror database. The user can check the parking price and make their reservation via mirror database, and data synchronization processor takes the responsibility to transfer related data to repository. In this case, the security of parking information is protected, as well as the information redundancy is reduced. Based on the real-time parking data, there are four specific applications in the iRev, including

Wi-Fi monitor, reservation authority, price decider and smart payment. (1) Wi-Fi monitor is designed to monitor and report on Wi-Fi Access Points. It monitors and reports on performance, availability and problems. (2) Reservation authority is responsible for verifying the reservation process and driver's identity. (3) Price decider is to determine the parking price based the parking state. (4) Mobile payment allows drivers to use their mobile phones to pay parking fee.

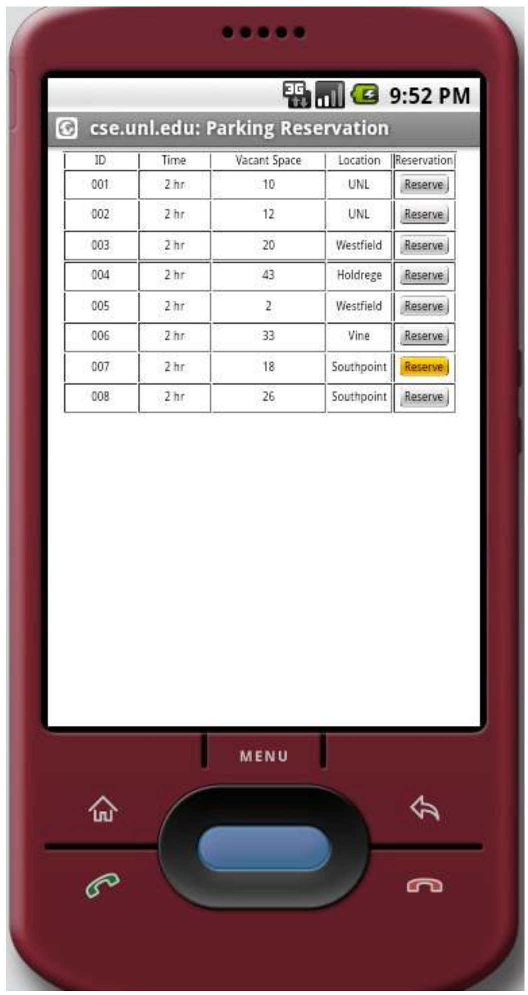

Figure 4.3: Architecture of Parking Management System

RSPS provides the web service to the drivers, as shown in Fig. 4.3 and 4.4. When the sensor network in parking lots detects the change of parking states, it sends the real-time sensing data to the parking info repository. Then, the data synchronization processor updates the associated data in mirror database based on parking info repository. The system dynamically updates the parking and reservation information on the website according to the data stored in a mirror database. The driver is able to obtain the real-time parking information from the

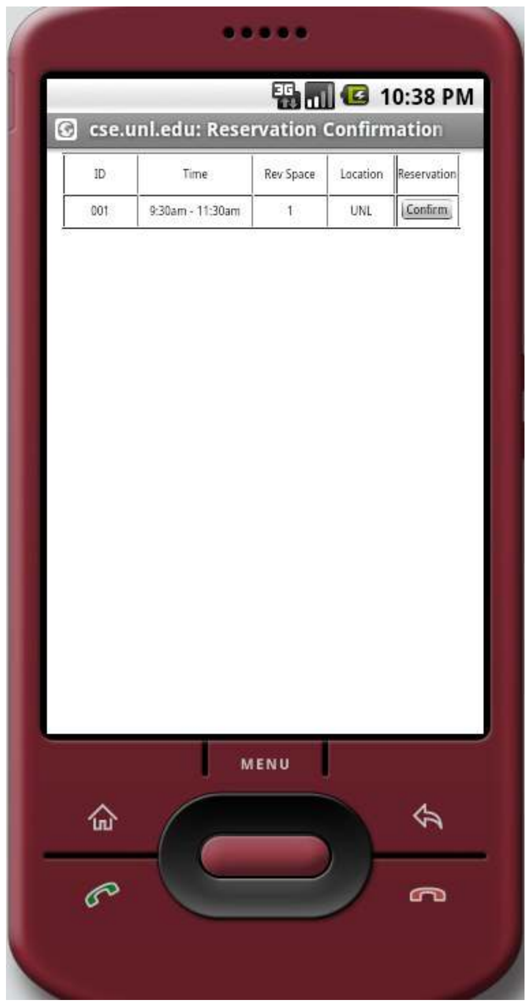

Figure 4.4: Architecture of Parking Management System

web server, as shown in Fig. 4.3. If the driver selects his/her desired parking lot, s/he is able to reserve a parking space in the selected parking lot. After verifying the driver's identity in reservation authority, the system updates the reservation information in the mirror database, and the driver receives the confirmation information, as shown in Fig. 4.4.

Chapter 5

Evaluation

In this chapter, we simulate the proposed Reservation-based Smart Parking (RSP) system based on real traffic traces and real-world parking map, and demonstrate the performance of the RSP in terms of the metrics shown in Section 2.

5.1 Simulator Design

In order to investigate the parking guidance policies and the proposed RSP system, we have to develop a simulator to import the real-world map and traffic traces, simulate users' parking behaviors and implement related parking strategies. Specifically, we use Java 1.5 to develop the main components, including dynamic pricing scheme, data access and *iRev* applications. For the data repository and minor database, we use MySQL. And we use JSP to implement the web service by using Apache Tomcat as the web environment. For the sensor program, we use TinyOS and nesC to develop specific applications.

5.1.1 Real Map Import

This simulator allows us to import a real-world map as the target area, and acquires the information from the map, e.g., distance and paths. Given the map, let $G = (N, A)$ be traffic network defined by a set N of nodes and a set A of edges, where N and A represent the set of blocks and the set of roads connecting blocks. With the parking map, we aggregate the parking lots in one block as a virtual parking lot. Therefore, each node has a (virtual) parking lot attached, and an edge has a specific value assigned to represent the distance between two blocks.

5.1.2 Parking Demand Modeling

In the simulation, we use the real-world traffic traces to generate the parking demand. Here the parking demand is the number of drivers who need parking spaces in the target area. However, in reality, it is difficult to collect the traffic traces for parking in the target area. Although the sensor network is deployed to monitor the incoming and outgoing traffic for parking in individual parking lot [16], [8], the traffic data from individual parking lot cannot represent the total traffic traces for parking in the whole area. Fortunately, we can employ the highway traffic traces to estimate traffic for parking, which are available from the Performance Measurement System (PeMS) at the University of California, Berkeley. Here we make a general assumption that real total traffic for parking is proportional to the highway traffic. Although not all of traffic pursuing parking spaces in target area are from highways, and not all highway traffic need to park in the target area, the highway case can simulate the state of total traffic for parking. We classify the total highway traffic into incoming traffic and outgoing traffic, which represent the traffic approaching to and leaving from the target area. The incoming traffic serves as the reference of parking demand. We use the driving distance within the target area to measure the traffic for parking. For calculating the driving distance, the vehicles begin to run the distance meters, once they enter the area, until reaching the selected parking lot. Moreover, as we discuss in Section 3, we use congestion factor l to represent the level of congestion condition. In the simulation, we use the traffic load to simulate the congestion condition. For instance, if $l = 1$, the traffic load is under normal condition. If $l = 2$, the traffic load is double the normal condition.

5.1.3 Simulator Implementation

In order to implement different parking policies in the simulation environment, we use object-oriented design to realize the interactions between objects (e.g., users and parking lots). Although there are thousands of autonomous drivers who behave differently, they have the same common concerns about the parking selection, including convenience degree and parking price. So the object-oriented design provides us a cost-effective way to implement different behaviors and common concerns of objects through structures within the program. Meanwhile, by providing the interface of the objects, it is easy to extend the simulator to other applications. Therefore, the simulator is developed not only for reservation policy and dynamic pricing scheme, but to simulate general strategies of parking selections.

5.2 Simulation Setup

In our simulation, we use the map of Los Angels Downtown as the target area, as shown in Fig. 5.1, which is surrounded by the interstate highways, I-101, I-110, I-10

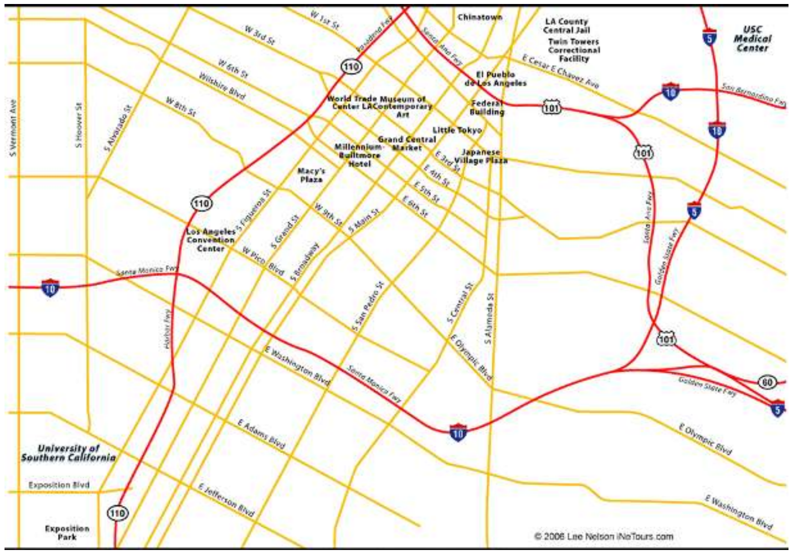

Figure 5.1: Map of Los Angeles Downtown

and I5. I-n this area, there are multiple typical districts including central business district, residential district, entertainment venues, which is one of busy areas in Los Angeles. This area is very representative in big cities. Furthermore, Fig. 5.2 illustrates the incoming and outgoing traffic in two different days. As we see, the peak time of incoming traffic is from 6am to 10am, and the rush hour of outgoing traffic is during 5pm to 8pm. It matches people's regular schedule, in the morning most people drive to work and go back home after 5pm. Therefore, the traffic trace is reasonable to generate the parking demand in the simulation. Furthermore, we assume that the users' budget distribution follows the Gaussian distribution at a certain range from 1 to 10. If the budget is less than 1, we force it to be 1, and if it is larger than 10, we set it to 10.

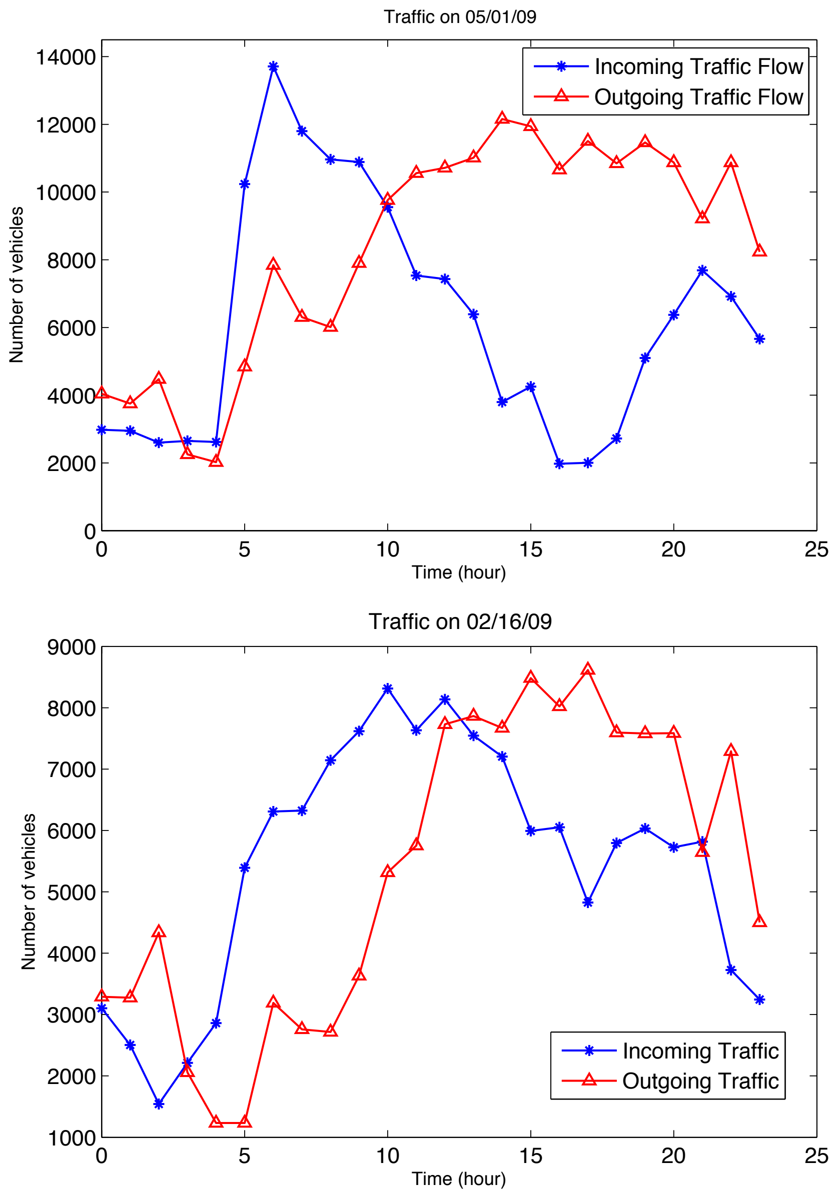

Figure 5.2: Incoming and Outgoing Traffic Flows

5.3 Experimental Results

The following experimental results illustrate the efficacy and feasibility of the proposed Reservation-based Smart Parking (RSP) system in a cost-effective way. We evaluate the effectiveness of reservation policy and dynamic pricing scheme in terms of following perspectives:

5.3.1 Traffic Searching for Parking

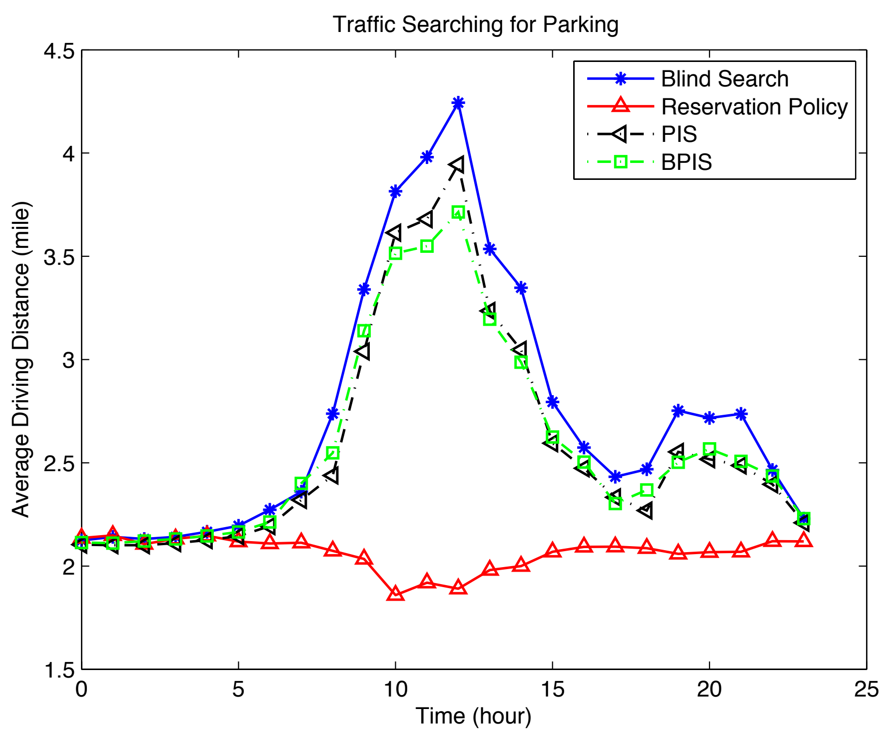

Figure 5.3: Traffic Searching for Parking Comparison under Different Parking Guidance Strategies

As we discuss in Chapter 2, Fig. 5.3 shows that the driving distance under blind search is the worst, especially during the peak hours; PIS and BPIS are better than blind search when traffic flows increase; and the reservation policy is the best compared with others. Note that, in this simulation, there is no pricing scheme implemented in reservation policy. An interesting observation of reservation policy is that the average driving distance is decreasing at peak time, rather than increasing. That is because, after users learn the states of parking lots, they tend to reserve the nearest parking lot to their destination. During the peak hours, most parking lots are almost fully occupied in central area. Consequently, users have to select the parking lots in surrounding area, which are near to their start points. Therefore, it results in the reduction of average driving distance during the peak hours.

Related to the dynamic pricing scheme, fix-price policy is option for the service

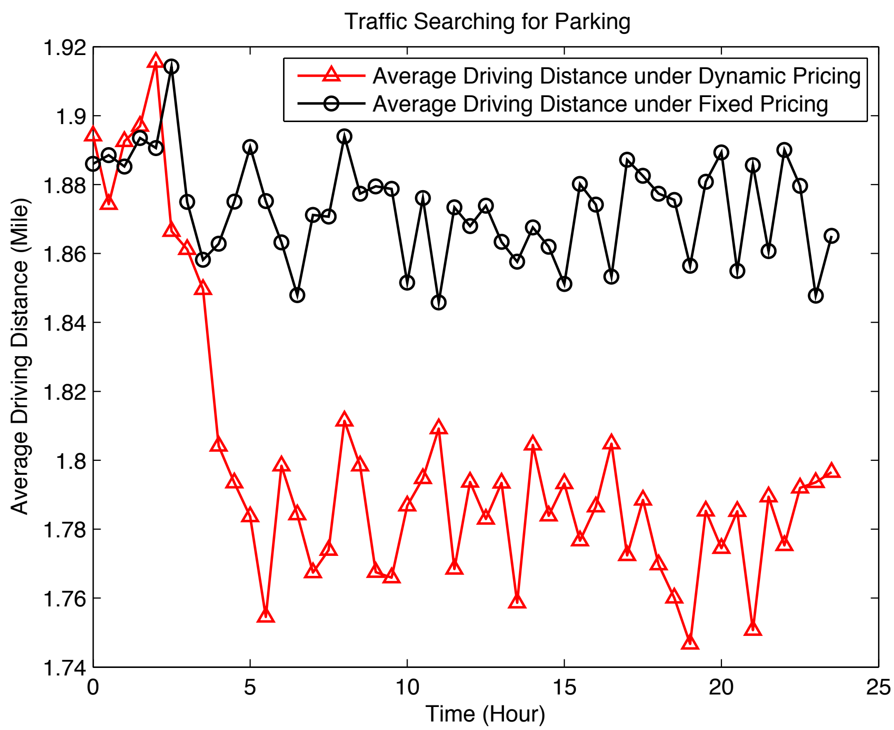

Figure 5.4: Traffic Searching for Parking under Different Pricing Schemes

provide. In order to compare the traffic searching for parking under these two different pricing options, we implement this simulation. In this simulation, both fixed price and basic price of dynamic price are set as default value ($1 for per time slot). For the dynamic pricing scheme, β_u, β_s, β_c are set to $0.5, 0.3, 0.2$, which represent the different weights for different price components. For user's utility function, v and κ are set to 1 and 0.3. As shown in Fig. 5.4, by implementing the dynamic pricing scheme, the average driving distance of all users for parking searching can be reduced. In general, a user under dynamic parking price will select a parking lot that can provide the highest benefit. In contrast, under fixed pricing, each user cannot learn the related parking information from the price and is only concerned about the walking distance. It allows selfish users to pursue the nearest parking lots to their destination without any limitation. As a result, the parking lots busy districts are fully occupied, which force part of users to drive more and waste their waste their gasoline. Contrarily, the occupancy rate in surrounding districts is much lower. It also causes the problem of load balancing. Fig. 5.4 shows that, during the initial periods, the performance of driving distance is similar under two different schemes. Then, with the traffic load increasing, the parking pricing is growing and the congestion price is charged to prevent further congestion. In response, some users switch their selections from the high-priced parking lots to others at cheap price. As the result, the parking demand is better balanced across all parking lots, resulting in the reduction of driving distance, compared with fixed-price scheme.

5.3.2 Revenue

We first compare the performance of revenue growth under proposed dynamic pricing and fixed pricing, at different price units. Fig. 5.5 shows the total revenues

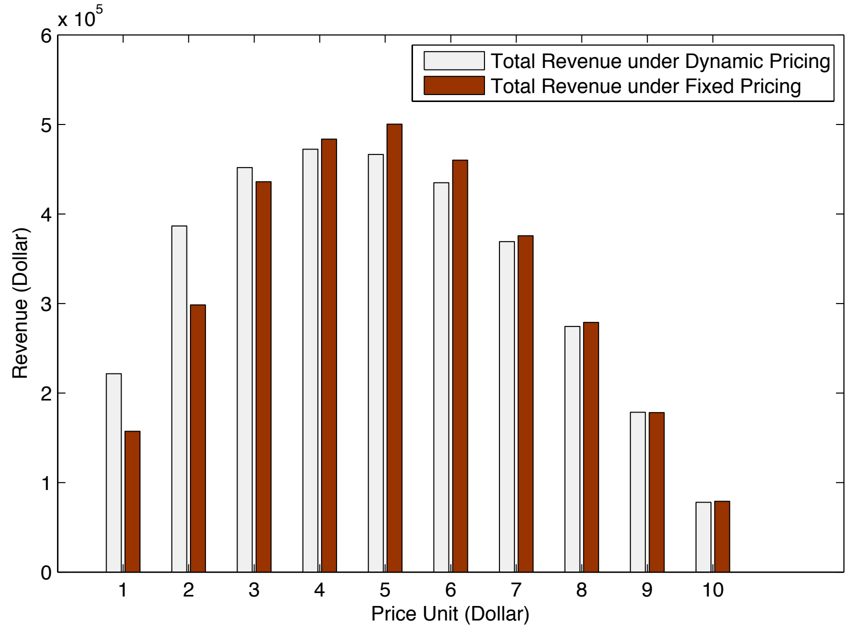

Figure 5.5: Revenue Comparison between Dynamic and Fixed Pricing

of all parking lots in the target area according to different pricing schemes implemented in reservation-based policy. Note that the price unit means basic price for dynamic pricing scheme, and unique fixed price for fixed pricing scheme. Depending on different price units, both kinds of pricing perform differently on revenue growth. Compared to fixed pricing, the proposed dynamic pricing can improve the revenue when the basic price is small. With the increasing of basic price, the revenue under dynamic pricing becomes similar with fixed price. Although the largest revenue is lower than fixed price (94.22%), dynamic pricing can let more valuable users with lower budgets find their desirable parking spaces. Since the users' budget constraints are under Gaussian distribution, higher basic price will cause more failure on parking searching and traffic congestion. Therefore, in real world, low price is more feasible considering the social welfare, which allows more users with lower budget get their parking spaces. In this case, the dynamic pricing can achieve better revenue, because it can adjust parking price dynamically based on parking condition, as well as let most users be satisfied.

Additionally, since setting the fixed price to obtain the most revenue is based the

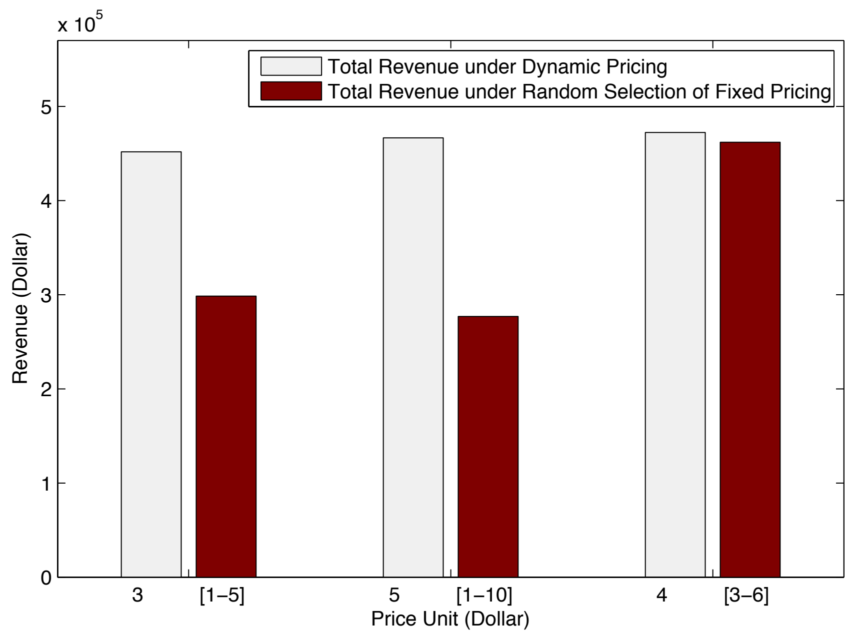

Figure 5.6: Revenue Comparison between Dynamic and Random Selection of Fixed Pricing

distribution of users' budgets, it is difficult to realize such distribution in the real world. So random selection of fixed pricing is considered as a potential option without the information of users' budget. As shown in Fig. 5.6, the revenue under random pricing depends on the random range. When the range selected is small enough, the revenue is getting close to the fixed price. With the increasing of random range, the performance of revenue growth becomes much worse than proposed dynamic pricing and fixed pricing. Therefore, this experimentation results show that the proposed dynamic pricing can adjust price according to real-time data to obtain more revenue and satisfy more users than fixed and random selection pricing, when the basic price is small. However, when the selection range is small enough, the provider obtains similar revenue under random selection and fixed price, but sacrifice the users' satisfaction.

The results in this simulation indicate that the proposed dynamic pricing scheme uses the real-time parking condition as users' feedback, takes advantage of users' differentiated needs for the improvement in revenue growth, as well as concerns users' satisfaction, relative to the fixed-price and random-price policies.

5.3.3 Service Differentiation

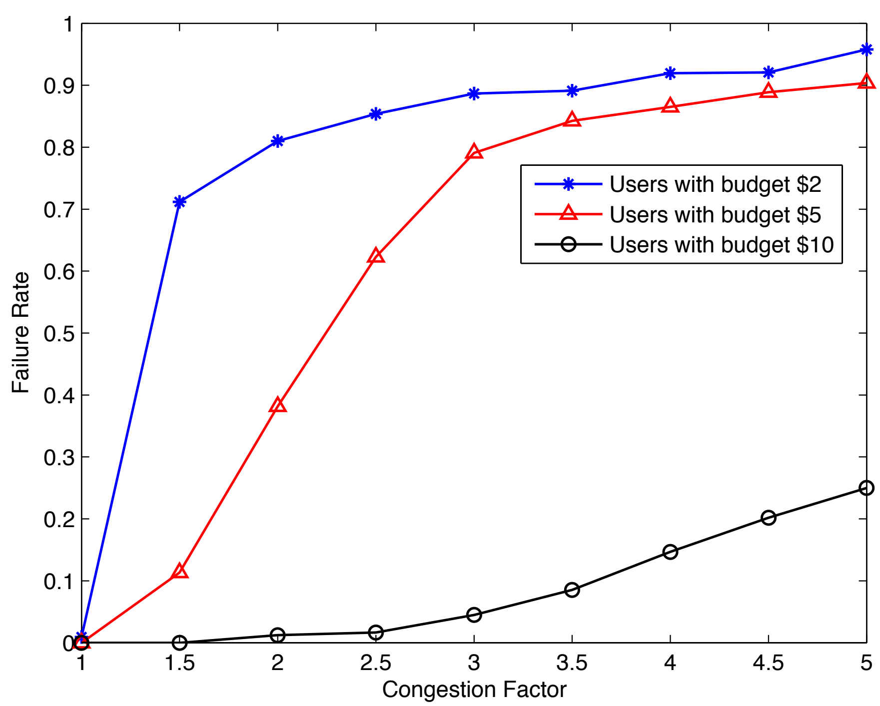

Figure 5.7: Failure Rates of Users with Different Budgets

The proposed dynamic pricing scheme can guarantee the service differentiation, even if the traffic congestion happens. In this simulation, we only implement the dynamic-price scheme, keep the basic price at the default value (which is $1 for per time slot), and vary the traffic load to check the failure rates of the users with budget $2, budget $5 and budget $10. The failure rate here is defined as the number of drivers who cannot find parking spaces versus the number of total drivers. As shown in Fig. 5.7, all failure rates of these users is seen to increase with the congestion factor, which is determined by traffic load in this simulation. Initially, under the default basic price, all users can find their desired parking spaces. With the load increasing, the failure rate of users with budget $2 soars firstly, and then more users with budget $5 start to be unable to find parking spaces. At the heavy load, the dramatic parking demand causes the higher failure rate of users with budget $10. However, when the congestion happens, the dynamic-price scheme can guarantee the quality of parking service for the users with higher budgets, compared with the users with low budgets. Furthermore, by adjusting the price dynamically, it stimulates users to moving to uncongested parking lots via lower price to help balance the traffic load.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In this thesis, we have developed a new Reservation-based Smart Parking (RSP) system to optimize parking management. We have proposed a dynamic pricing scheme for satisfying the different needs of drivers and service providers, which is based on real-time parking information. The pricing scheme is integrated with the proposed RSP system in which parking price is dynamically adjusted in response to the relationship of demand and supple and congestion level. Upon receiving parking prices, drivers make their reservations to maximize their benefits according to the utility function. Based on the obtained results from our simulation study, we conclude that the proposed RSP system increases the revenue for service providers, provides service differentiation for users with different needs, alleviates traffic congestion caused parking searching and reduces the amount of traffic searching for parking.

6.2 Future Work

In this section, we discuss future work of the model implementation.

6.2.1 Synchronization

In the proposed RSP system, sensing system is responsible for collecting parking information periodically. Synchronization of the parking states in different parking lots is required. Along this direction, the authors in literature [14] proposed a fully localized diffusion-based method to achieve full scalability, and Jana et al [26] introduced lightweight tree-based synchronization (LTS) algorithm to operate the node failures. In the proposed system, the management system collects the parking information from individual parking lots, and generates the parking guidance signal (i.e., parking price). Hence, with the centralized management system, it is trivial to achieve the clock-synchronization of the sensed data.

6.2.2 System Deployment

In the real world, it is impossible to make all of drivers adopt the proposed RSP system at once. Increasing the deployability is an important concern. Fortunately, by implementing the reservation policy and dynamic pricing scheme, the proposed RSP system is in favor of the drivers using such system, when compared to users without using the system. Hence, it provides enough incentive for drivers to adopt the system.

6.2.3 Security and Privacy

One of the concerns in our proposed RSPS is the security of communication and users privacy. Based on a secure symmetric encryption algorithm [17], all communication between service providers and users are encrypted. Additionally, to protect users' privacy, we may use virtual identifier for each user when the user is authenticated in the system. As a result, the real identifiers of users are hidden from the adversary.

Bibliography

[1] Open spot. http://openspot.googlelabs.com/.

[2] Solutions for improving city operations. http://www.streetlinenetworks.com/.

[3] The global warming survival guide. *Time magazine*, 2007.

[4] *Transportation Energy Databook*. U.S. Department of Energy, 2010.

[5] Ella M. Atkins. Cyber-physical aerospace: Challenges and future directions in transportation and exploration systems. In *Technical Report CMU/SEI-2011-TR-002*, 2011.

[6] R. Baheti and H. Gill. Cyber-physical systems. In *The Impact of Control Technology*, 2011.

[7] Murat Caliskan, Daniel Graupner, and Martin Mauve. Decentralized discovery of free parking places. In *Proc. of the Third ACM International Workshop on Vehicular Ad Hoc Networks (VANET'06)*, 2006.

[8] Jatuporn Chinrungrueng, Udomporn Sunantachaikul, and Satien Triamlumlerd. Smart parking: an application of optical wireless sensor network. In *Proceedings of Application and the Internet Workshops*, 2007.

[9] Edmund M. Clark, Bruce Krogh, Andre Platzer, and Raj Rajkumar. Analysis and veri cation challenges for cyberphysical transportation systems. In *NITRD National Workshop for Research on Transportation Cyber-Physical Systems: Automotive, Aviation, and Rail*, 2008.

[10] Michal Feldman, Kevin Lai, and Li Zhang. A price-anticipating resource allocation mechanism for distributed shared clusters. In *Proceedings of the 6th ACM conference on Electronic commerce*, 2005.

[11] F.P.Kelly, A.K.Maulloo, and D.K.H.Tan. Rate control for communication networks: shadow prices, proportional fairness and stability. *Operational Research Society*, 49:237–252, 1998.

[12] Alain L. Kornhauser. About prospect eleven and the DARPA project. *J. Robot. Syst.*, 23(9):745–753, 2006.

[13] I. Lee and O. Sokolsky. Medical cyber physical systems. In *Design Automation Conference (DAC 2010)*, 2010.

[14] Qun Li and Daniela Rus. Global clock synchronization in sensor networks. In *Proceedings of IEEE INFOCOM'04*, 2004.

[15] Todd Litman. Smart transportation emission reduction strategies. 2011. http://www.vtpi.org/ster.pdf.

[16] Rongxing Lu, Xiaodong Lin, Haojin Zhu, and Xuemin (Sherman) Shen. SPARK: A new VANET-based smart parking scheme for large parking lots. In *Proceedings of IEEE INFOCOM'07*, 2007.

[17] Wenbo Mao. *Modern Cryptography: Theory and Practice*. Prentice Hall, 2003.

[18] Suhas Mathur, Tong Jin, Nikhil Kasturirangan, Janani Chandrashekharan, Wenzhi Xue, Marco Gruteser, and Wade Trappe. ParkNet: Drive-by sensing of road-side parking statistics. In *MobiSys'10*, 2010.

[19] B. McMillin, C. Gill, M. L. Crow, F. Liu, D. Niehaus, A. Potthast, and D. Tauritz. Cyber-physical systems distributed control: the advanced electric power grid. *Electrical Energy Storage Applications And Technologies*, 2007.

[20] O'Sullivan and Steven M. Sheffrin. *Economics: Principles in action*. Pearson Prentice Hall, 2006.

[21] Ragunathan (Raj) Rajkumar, Insup Lee, Lui Sha, and John Stankovic. Cyber-physical systems: The next computing revolution. In *Design Automation Conference*, 2010.

[22] Jake Reisdorff, Aldo Arizmendi, and Jason Armstrong. Parking lot detection proposal.

[23] Krishna Sampigethaya, Radha Poovendran, and Linda Bushnell. Secure operation, control and maintenance of future e-enabled airplanes. *IEEE special issue on Aviation Information Systems*, 96(12):1992–2007, December 2008.

[24] Susan A. Shaheen and Caroline J. Rodier. Smart parking management field test: A bay area rapid transit (BART) district parking demonstration. *UCD—ITS—RR—05—02*, 2005.

[25] Donald C. Shoup. Cruising for parking. *Transport Policy*, 13:479–486, 2006.

[26] Jana van Greunen and Jan Rabaey. Lightweight time synchronization for sensor networks. In *Proceeding ACM WSNA'03*, 2003.

[27] Hal R. Varian. *Microeconomic Analysis*. New York: Norton, 2003.

[28] Xin Wang and Henning Schulzrinne. Pricing network resources for adaptive application. *IEEE Transactions on Networking*, 2005.

[29] Paul Steely White. No vacancy: Park slope's parking problem. *Transportation alternatives*, 2007. http://www.transalt.org/newsroom/releases/126.

[30] Wayne Wolf. The good news and the bad news. *IEEE Computer*, 10.1109/MC.2007.404, 2007.

[31] Daniel Work, Alexandre Bayen, and Quinn Jacobso. Automotive cyber physical systems in the context of human mobility. In *National Workshop on High-Confidence Automotive Cyber-Physical Systems*, 2008.

[32] Daniel B. Work and Alexandre M. Bayen. Impacts of the mobile internet on transportation cyberphysical systems: Traffic monitoring using smartphones. In *National Workshop for Research on High-Confidence Transportation Cyber-Physical Systems: Automotive, Aviation and Rail*, 2008.