SmartParking: A Secure and Intelligent Parking System

Observations from the IEEE IV 2010 Symposium

***Abstract*–**Parking is costly and limited in almost every major city in the world. Innovative parking systems for meeting near-term parking demand are needed. This paper proposes a novel, secure, and intelligent parking system (SmartParking) based on secured wireless network and sensor communication. From the point of users' view, SmartParking is a secure and intelligent parking service. The parking reservation is safe and privacy preserved. The parking navigation is convenient and efficient. The whole parking process will be a non-stop service. From the point of management's view, SmartParking is an intelligent parking system. The parking process can be modeled as birth-death stochastic process and the prediction of revenues can be made. Based on the prediction, new business promotion can be made, for example, on-sale prices and new parking fees. In SmartParking, new promotions can be published through wireless network. We address hardware/software architecture, implementations, and analytical models and results. The evaluation of this proposed system proves its efficiency.

Digital Object Identifier 10.1109/MITS.2011.940473
Date of publication: 6 April 2011

1939-1390/11/$26.00©2011IEEE

Gongjun Yan
Indiana University Kokomo
Kokomo, IN 46904 USA
E-mail: goyan@iuk.edu

Weiming Yang
Chongqing Technology & Business University
Chongqing 400067, China
E-mail: ywmls@hotmail.com

Danda B. Rawat
Stephan Olariu
Old Dominion University
Norfolk, VA 23529 USA
E-mails: drawa001@odu.edu and olariu@cs.odu.edu

I. Introduction

Parking is limited in almost every major city in the world—leading to traffic congestion, air pollution, and driver frustration. For example, the Manhattan Central Business District (CBD) has 109,222 off-street public parking spots [1], for a ratio of approximately one off-street public spot for every 16 CBD workers. Yet, often parking spots are wasted. In large parking lots, a driver may exit the lot without knowing about new spots that have just become vacant. Finding an empty parking spot may also lead to driver frustration if another car takes the spot before the driver can reach it.

Thus, innovative parking systems for meeting near-term parking demand are needed. With wireless communications, computer, control, and electronics technologies, intelligent service-oriented parking management can improve parking space utilization and improve driver experience while decreasing drivers' frustration. Our motivation is to fill the near-term parking demand using the wireless technology. The contributions of our system include: 1) increasing space utilization, 2) improving drivers' experience, and 3) providing intelligent management. From the point of users' view, SmartParking system which is a secure and intelligent parking service. Parking information, order information, and vehicle information are collected and transported by sensor detection and the wireless network. The proposed infrastructure prevents most security/privacy attacks. The parking navigation is convenient and efficient. Drivers can view and reserve a parking spot on the fly. The parking process can be a straightforward and non-stop process. From the point of management's view, SmartParking is an intelligent parking system. The parking process can be modeled as birth-death stochastic process and the prediction of revenues can be made. Based on the prediction, new business promotions can be made. For example, promotion prices (on-sale prices) and new parking plans can be advertised and broadcasted to all the passing vehicles without extra costs. In SmartParking, new promotions can be published through wireless network. We address hardware/software architecture, implementations, and analytical models and results.

The rest of the paper is organized as follows. The related work in literature is presented in Section II. Then, the architecture and operations of the secure and intelligent parking service are described in Section III. In Section IV and V, the management and the maintenance of the parking system are introduced. Simulations are performed in Section VI to show the advantages of the system. Finally, we will conclude the paper in Section VII.

II. Related Work

Caliskan et al. [2] proposes a parking system in which parking automats are the producers of resource reports. The infrastructure uses IEEE 802.11 to broadcast these reports as raw text packets. The report packet size is 92 bytes. The assumption is that parking automats are able to sense their occupation status at any moment. Each vehicle starts with an empty cache, i.e., it has not obtained any resource report. During its trip, it receives resource reports from parking automats or other vehicles. Received reports are integrated into a vehicle's cache. These reports are aggregated and disseminated among vehicles. The decision strategy of which parking lot is used is based on two influencing parameters: the age of a resource and the distance to a resource. This system is not concerned with security or privacy issues, which are important.

The basic infrastructure of a parking system relies on devices to detect if parking spaces are occupied. Several approaches are employed to detect reliable information. First wired sensors are widely used [3]: 1) inductive loops, 2) pneumatic road tubes, 3) magnetic sensors, 4) piezo-electric sensors, 5) weigh-in-motion systems. Wolff et al. [4] use the Earth's magnetic field to detect parking spaces. These devices or sensors are physically wired to the control computers. One shortcoming of the wired sensor systems is that long and complicated wiring is required from parking lots to the central control unit. Also, the cost for developing this system is high because a large amount of sensor units are required. Therefore some wireless sensors can be applied to the parking space detection. Tang et al. [5] developed such a system using Crossbow Mote products and the extended Crossbow XMesh network architecture. Stiller et al. [6] proposed Cognitive Automobiles which have intelligence to handle some events in real scenarios. Benson et al. [7] propose RF transceiver and antenna with an ATMega 128L micro-controller system. Third, image processing is applied to detect the vehicles [8], [9]. Funck et al. [10] uses images to detect the parking space. These methods, however, may incorrectly detect parking vehicles. One example is that a vehicle temporally uses one slot to park in another slot, or that a vehicle just happens to be in the intersection of these sensors. Panayappan et al. [11] propose a parking system in VANET to locate the available parking lots and spots. This system uses roadside units to relay parking messages and GPS to locate vehicle position. Roadside units maintain the security certificates and parking information. The security issue addressed in this paper is to ensure fare-play among drivers by encryption and frequently sensing the available spots. The greedy drivers are prevented from gaining more advantage from the system by lying. But there are some security problems. For example, a roadside attacker pretending to be a vehicle can reserve as many slots as he wishes. In our system, all the communications are triggered by physical pressure on a sensor-based detector/belt and are enabled by short range signals. There is no way to launch a roadside attack.

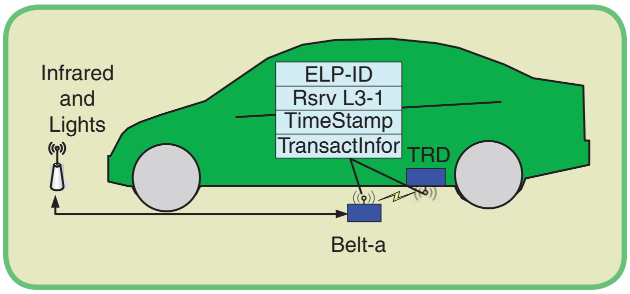


FIG 1 Vehicle detection and transaction confirm.

III. Secure and Intelligent Parking Service

From the point of user's view, the parking system is secure, privacy-preserved, and intelligent parking system. This parking system can provide non-stop parking services [12].

A. Architecture

1) Hardware Architecture

Each vehicle is predeployed a short range wireless transceiver and a simple processor. The transmission range is $1m$. It can be one of the current short range devices, such as zigbee devices, bluetooth devices and infrared devices. Both wireless transceiver and processor are fitted into an EDR.

The infrastructure for parking provider consists of wireless transceivers, parking belts, Infrared Device (IFD), and control computer. The wireless transceiver can be WiFi wireless network or a Wirless Lan (WLan) network. It is to transmit the parking information (for example, the capacity of empty parking spots, the position list of empty parking spots, etc.) and reserving information. When a driver who reserved a parking spot arrives at the parking area, the entrance booth prints out a check-in confirm card with a reserved parking spot number. The parking belts, Infrared Device (IFD), as shown in Fig. 1, will work together to check-in a vehicle. The IFD at the parking spot connects to a signal light. A yellow light means empty spot. A blue light means filled spot. A red light means misfilled vehicles which will be charge a certain amount of money. To detect whether the parking space is occupied, we use both infrared device IFD and two belts, shown in Fig. 1. Belt-a is at the middle of the slot. When front wheels of a vehicle press on Belt-a, the detection process is activated and a count-down timer is set. The transceiver at Belt-a sends out a "hello" message contained belt ID. The vehicle sends out the parking check-in information after it receives the "hello" message. All these communications are on very low power (transmission range is less than 1 meter). Belt-a validate the check-in information and set a signal light to signal the driver it is a wrong slot to park or not. If the driver misparks the vehicle, a red light is on. Otherwise, a blue light is on and a message sent from Belt-a will alarm the parking maintenance manager. To void the belts are pressed by something else, we use infrared device IFD to double check if there is a vehicle. To prevent that some vehicles may happen to press on the belts or just use a slot to park in another slot, we verify the parking vehicle once more when the count-down timer expired.

B. Software Architecture

In software architecture, we propose several modules shown in Fig. 2 [12]. The architecture consists of four modules:

- **Driver Module** is responsible for the communication with hardware devices. The driver module consists of communication driver and sensor driver for belts, communication driver for vehicles' short range transceiver, and IFD driver for vehicle detection.
- **Communication Module** receives and transmits messages between sender and receiver. For Vehicle-to-Infrastructure (V2I), this module simplifies the communication process and performs error control, for example verifying the checksum and correcting errors. In general, the purpose is fast communication speed and enhanced message correctness because the communication response time is strict.
- **Function Module** is a core module of the parking system. Thanks to the subscription to driver module and communication module, the function module can directly talk to hard devices and transmit/receive data without having to know the detail of the driving protocol.
- **Application Module** is to manage the whole parking system. The main function of the application includes account management (cash, credit/debit management), operation management, and maintenance management.

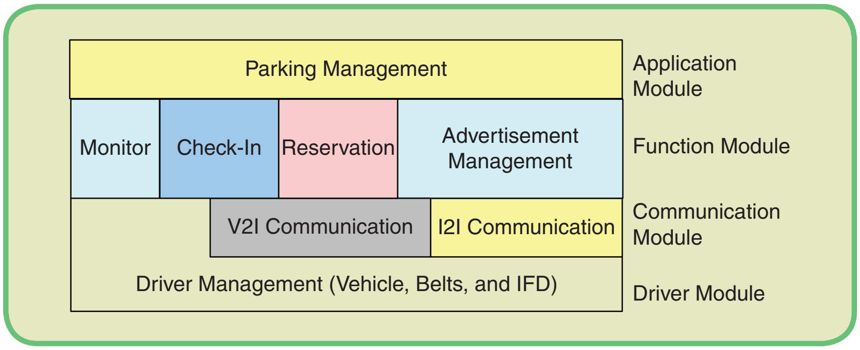


FIG 2 SmartParking software architecture.

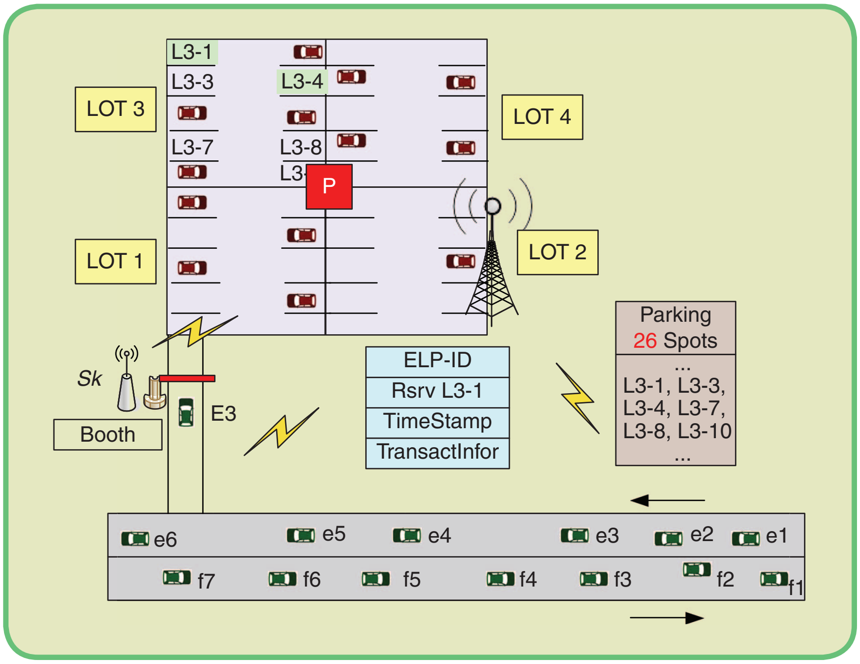


FIG 3 SmartParking scheme.

C. Reaction Scheme

1) Advertisement Publishing

A computer center at the parking booth frequently keeps parking capacity, a map of empty spot in the parking area. These vacant spot information is obtained by the wireless network. All information are encrypted during the communication.

Advertisement of the parking spot information is published by the wireless communication network. The infrastructure for the parking spot advertisement consists of several wireless transceivers. The topology and the number of the transceiver depend on the geography of the parking garage. In Fig. 3, we deploy one transceiver tower at the parking site. The transceiver at the parking site is called *base station* because it is the center of the transaction. The base station transmits parking information to vehicles passing by. The parking information is signed by the private key. Vehicles will receive a copy of the parking advertisement and validate the parking information by the public key. The advertisement includes the parking site location, the total number of empty spots (the capacity of the empty spots), and the list of empty spots.

2) Reserve Parking Lot

The terminals (e.g., PDAs, cell phones, and laptops) of drivers can receive messages sent from the base station. The format of the parking information is Extensible Markup Language (XML). Therefore these terminals can be parsed on all sorts of terminals and friendly display the

FIG 4 SmartParking user interface. A user can view the empty spots and reserve one spot. The reserved spot in this figure is at lot 3 number 4 spot: L3-4.

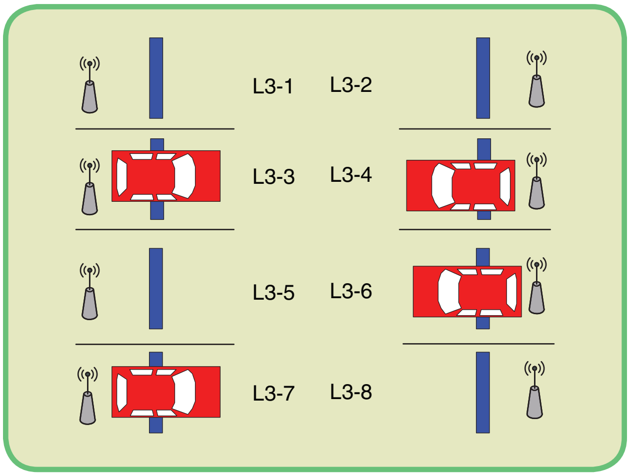


FIG 5 Parking spot detail.

empty spots. An interface of the parking spots is shown in Fig. 4.

The process of this reservation order is the following: A vehicle e_3 is passing the parking site. It picks up an advertisement. If e_3 select one of parking spot $L3$–4 shown in Fig. 3, the user terminal/client program will send a reservation request to the base station where the request will be processed. The request will be encrypted by the public key of the parking site. Each reserved order consists of a vehicle's Electronic License Plate (ELP), reserved parking spot number, a time stamp when it is ordered, and *transaction expire time*. The *transaction expire time* is a count-down time which is a maximum time to reserve the parking spot. If the vehicle ordered a spot but did not show up before the transaction expire time, the reserved spot is reopened to other vehicles.

If a vehicle does not order any parking spot and directly drive to the parking site, the parking entry booths will randomly pick an empty spot to the vehicle. If orders collision happens, new randomly selected parking spots are picked from the empty spots to solve the order collisions.

3) Cancel Transaction

If a driver decides to cancel a parking reservation, the cancel process is similar with the reservation process. A cancel order is sent to the base station where the cancel order is processed. In a special scenario, drivers may not cancel transaction. However, the spots reserved by these drivers will be freed when the transaction expire time is past. To prevent this scenario, a certain amount of penalty fee can be charged because these drivers hold parking resources for a period of time.

4) Parking Check In

When a vehicle e_3 which has a reservation order arrivals the parking entry booths S_k, the vehicle transceiver can communicate with the booth transceiver and report the encrypted reservation order to the booth transceiver. The reservation order is transmitted to the control center where the transaction is validated, and map guidance to the parking spot is calculated and linked to the spot. The control center then transmits the confirmation and map guidance to the booths where the information is printed.

The e_3 uses the map guidance to find the parking spot. Several devices, as shown in Fig. 1, can detect and validate the vehicle. A top overview of a parking lot is shown in Fig. 5. An infrared device can detect a vehicle e_3 taking the spot and set a count-down waiting time (5 min) for fully finishing parking. A belt (Belt-a in Fig. 1) inside the parking slots is embedded. The communication initiates when front wheel of the parking vehicle press on the Belt-a. The vehicle transceiver in EDR reports the encrypted parking confirmation to the transceiver in Belt-a. The Belt-a and infrared device connect each other and validate if the parked vehicle is a valid vehicle. When the count-down waiting time reach to zero, the Belt-a and infrared device are activated to double check if the parking vehicle is invalid/misparking. The vehicle' transceiver will report the confirmation card data to the Belt-a. The reason we use the belt and infrared devices is that other vehicles may happen to temporally use a slot to move into a slot or back a vehicle. We want to double check if there is really a parking vehicle with valid parking confirmation card. A maintenance warning is reported to the maintenance center (or manage center) and the user be charged a certain amount of fine if the parking vehicle is confirmed misparking. No matter the user does normal parking or misparking, a message will be reported to the control center that the spot is taken. The report consists of parking start timestamp, parking validation (valid parking or invalid parking), confirmation card data.

5) Payment

The charge for parking is based on parking time, reservation fee, and misparking penalty fine. Each of them has a rate. The parking time is the duration of entry time and exit time. Reservation fee and misparking penalty fine are reported through the parking communication network discussed before.

IV. Intelligent Parking Management

From the point of management's view, SmartParking is an intelligent parking system. We model the parking process as a birth-death stochastic process which predicts the revenue. The birth of parking means that a vehicle enters a parking spot and occupies the spot for a certain period of time t. The death of parking means that the vehicle leaves the parking spot and the parking spot becomes vacant. The birth rate and the death rate of vehicles can be measured by using traffic detectors [13] and laser scanner and video camera [14], [15]. The notation of the birth-death process can be found in Appendix. By modeling the parking process as a birth-death process, we can predict the revenue of the parking site based on a certain parking service (for example, flat rate, economy spots, and business spots). We can study the optimal parking services and find the best parking services. The detail of the services can be broadcasted to the vehicles passing by the parking site through wireless networks.

A. Parking Process Analysis

Consider a SmartParking site where the number of available parking slots is so large that for all practical purposes it can be considered infinite. Denote by $X(t)$ the number of slots in use at time t. Then, our physical intuition is not violated by assuming that $\{X(t); t \geq 0\}$ is a birth and death process. It also seems reasonable to assume that, for all $t > 0$, $h > 0$ and $i = 0, 1, \ldots$. The slot is in use at λ.

$$P\{X(t+h) = i+1 | X(t) = i\} = \lambda h + o(h),$$
$$P\{X(t+h) = i-1 | X(t) = i\} = \mu_i h + o(h)$$

because the probability that a car parking will occur in $(t, t+h)$ is independent of the number of busy slots at time t. It is obvious for the second equation as well.

Let us calculate $p_i(t)$ under the assumption that

$$\mu_i = i\mu$$

In this case, the system of difference-differential equations becomes

$$p_0'(t) = -\lambda p_0(t) + \mu p_1(t),$$
$$p_j'(t) = \lambda p_{j-1}(t) - (\lambda + j\mu) p_j(t) + \mu(j+1) p_{j+1}(t)$$

To solve this, we can use the generating functions. Set

$$g(t, u) = \sum_{j=0}^{\infty} p_j(t) \mu^j$$

then taking into account the previous two differential equations, we obtain,

$$\begin{aligned} \frac{dg(t,u)}{dt} &= \sum_{j=0}^{\infty} p_j'(t)\mu^j \\ &= -\lambda p_0(t)(1-\mu) + \mu p_1(t)(1-\mu) - \lambda p_1(t)(1-\mu)\mu \\ &\quad (1-\mu)\mu + 2\mu p_2(t)\mu(1-\mu) - \ \ldots \\ &= -\lambda(1-\mu)\sum_{j=0}^{\infty} p_j(t)\mu^j + \mu(1-\mu)\sum_{j=1}^{\infty} j p_j(t)\mu^{j-1} \\ &= -\lambda(1-\mu) g(t,\mu) + \mu(1-\mu)\frac{dg(t,\mu)}{d\mu} \end{aligned}$$

Thus, the generating function $g(t, \mu)$ satisfies the linear partial differential equation

$$\frac{dg(t,\mu)}{d\mu} - \mu(1-\mu)\frac{dg(t,\mu)}{d\mu} = -\lambda(1-\mu) g(t,\mu)$$

Suppose that $X(0) = i_0$, then,

$$g(0, \mu) = u^{i_0} \tag{1}$$

Solving this equation by standard methods and using the initial condition (1), we obtain

$$g(t,\mu) = [1 - (1-\mu)e^{-\mu t}]^{i_0} \exp\left[-\frac{\lambda}{\mu}(1-\mu)(1-e^{-\mu t}) \right] \tag{2}$$

Lemma 1

We now expand (2) to obtain $p_j(t)$ which represents the probability that the number 5 H of parking cars is j at time t.

$$p_j(t) = \exp\left\{ -\frac{\lambda}{\mu}(1-e^{-\mu t}) \right\} \sum_{k=0}^{\min\{i_*, j\}} \binom{i_0}{k} \binom{\lambda^{j-k}}{\mu} \times \frac{e^{-\mu t k}\,(1-e^{-\mu t})^{i_0+j-2k}}{(j-k)!} \tag{3}$$

where $j = 0, 1, \ldots$

Proof

For the first part of (2), we can write

$$\begin{aligned} \text{first} &= [1 - (1-\mu)e^{-\mu t}]^{i_0} \\ &= [1 - e^{-\mu t} - \mu e^{-\mu t}]^{i_0} \\ &= \sum_{k=0}^{i_0} \binom{k}{i_0} (1-e^{-\mu t})^{i_0-k} (\mu e^{-\mu t})^k \\ &= \sum_{k=0}^{i_0} \binom{k}{i_0} (1-e^{-\mu t})^{i_0-k} (e^{-\mu t})^k \mu^k \end{aligned}$$

For the second part of (2), we can write

$$\text{second} = \exp\left[-\frac{\lambda}{\mu}(1-\mu)(1-e^{-\mu t})\right]$$
$$= \exp\left[-\frac{\lambda}{\mu}(1-e^{-\mu t}) + \frac{\lambda}{\mu}\mu(1-e^{-\mu t})\right]$$
$$= \exp\left\{-\frac{\lambda}{\mu}(1-e^{-\mu t})\right\}\exp\left\{\frac{\lambda}{\mu}\mu(1-e^{-\mu t})\right\}$$
$$= \exp\left\{-\frac{\lambda}{\mu}(1-e^{-\mu t})\right\}\sum_{j=0}^{\infty}\frac{\frac{\lambda^j}{\mu}(1-e^{-\mu t})^j}{j!}\mu^j$$
$$= \sum_{j=0}^{\infty}\exp\left\{-\frac{\lambda}{\mu}(1-e^{-\mu t})\right\}\frac{\frac{\lambda^j}{\mu}(1-e^{-\mu t})^j}{j!}\mu^j$$

Since $g(t,\mu) = \mathit{first} \cdot \mathit{second}$, we can obtain

$$g(t,\mu) = \left[\sum_{j=0}^{\infty}\exp\left\{-\frac{\lambda}{\mu}(1-e^{-\mu t})\right\}\frac{\frac{\lambda^j}{\mu}(1-e^{-\mu t})^j}{j!}\mu^j\right]$$
$$\cdot\left[\sum_{k=0}^{i_0}\tbinom{k}{i_0}(1-e^{-\mu t})^{i_0-k}(e^{-\mu t})^k\mu^k\right]$$
$$= \left[\sum_{j=k}^{\infty}\exp\left\{-\frac{\lambda}{\mu}(1-e^{-\mu t})\right\}\frac{\frac{\lambda^{j-k}}{\mu}(1-e^{-\mu t})^{j-k}}{j-k!}\mu^{j-k}\right]$$
$$\cdot\left[\sum_{k=0}^{i_0}\tbinom{k}{i_0}(1-e^{-\mu t})^{i_0-k}(e^{-\mu t})^k\mu^k\right](\textit{change variables})$$
$$= \sum_{j=k}^{\infty}\exp\left\{-\frac{\lambda}{\mu}(1-e^{-\mu t})\right\}\sum_{k=0}^{\min\{i_0,j\}}\binom{i_0}{k}\left(\frac{\lambda^{j-k}}{\mu}\right)$$
$$\times\frac{e^{-\mu tk}(1-e^{-\mu t})^{i_0+j-2k}}{(j-k)}\mu^j$$
$$= \sum_{j=k}^{\infty}p_j(t)\mu^j$$

Therefore, we can obtain $p_j(t)$, as claimed.

$$p_j(t) = \exp\left\{-\frac{\lambda}{\mu}(1-e^{-\mu t})\right\}\sum_{k=0}^{\min\{i,j\}}\binom{i_0}{k}\left(\frac{\lambda^{j-k}}{\mu}\right)$$
$$\times\frac{e^{-\mu tk}(1-e^{-\mu t})^{i_0+j-2k}}{(j-k)!}$$

Note that the first term on the right side of (2) is the probability generating function of the Binomial distribution with $p = \exp\{-\mu t\}$, whereas the second term is the probability generating function of the Poisson distribution with mean value

$$\Lambda(t) = \frac{\lambda(1-e^{-\mu t})}{\mu}$$

Therefore,

$$X(t) = X_0(t) + X_1(t) \tag{4}$$

where $X_0(t)$ is Binomial component, $X_1(t)$ is a Poisson component, and $X_0(t)$ is independent of $X_1(t)$ for all $t \geq 0$.

Lemma 2

$$E\{X(t)\} = i_0e^{-\mu t} + \frac{\lambda}{\mu}(1-e^{-\mu t}).$$

Proof

From (4), we know that $X(t)$ is determined by $X_0(t)$ and $X_1(t)$. From (2) and Lemma (1), we know $X_0(t)$ is Binomial distribution:

$$X_0(t) \sim \mathit{Binomial}(i_0, e^{-\mu t})$$

Therefore, the expectation of $X_0(t)$ is

$$E\{X_0(t)\} = i_0e^{-\mu t}$$

Similarly, from Lemma (1), we know $X_1(t)$ is Poisson distribution:

$$X_1(t) \sim \mathit{Poisson}\left(\frac{\lambda}{\mu}(1-e^{-\mu t})\right).$$

Therefore, the expectation of $X_1(t)$ is

$$E\{X_1(t)\} = \frac{\lambda}{\mu}(1-e^{-\mu t}).$$

From (4), we know

$$E\{X(t)\} = E\{X_0(t)\} + E\{X_1(t)\}$$
$$= i_0e^{-\mu t} + \frac{\lambda}{\mu}(1-e^{-\mu t}).$$

B. Parking Class Model

The whole parking site is partitioned into two service classes: the economy and the business. The economy parking is less quality of service and fewer fees. For example, the distance from the parking economy spots to the gate is much longer than the one from the business spots to the gate. The business parking is more quality of service but more expensive. The quality of service can be measured by the resources, for example, valet parking, the bigger space of the parking slot, more convenience of parking slot location, etc. We will use the analogy that the airline seats (economy and business) are like parking spots (economy and business). We can assume the economy parking has more parking slots in the economy parking than that in the business parking. Fig. 6 shows the parking classes.

Suppose we run the parking site for a long enough period of time. We can do simple statistics to know the average arrival rate of parking vehicles and the exit rate of vehicles. We use λ_1 to denote the arrival rate of parking vehicles in the economy parking site, μ_1 to the exit rate of vehicles in the economy parking site, λ_2 to the arrival rate of parking vehicles in the business parking site and μ_2 to the exit rate in the business parking rate, N_1 to the parking capacity of the economy site and N_2 to the parking capacity of the business site. We can model the parking classes as Poisson processes, specifically, two birth-death stochastic processes, as shown in Fig. 7.

There are four possible cases for the status of the parking slots at any time t. Case one is that both the economy parking site and the business parking site are not full. Case two is that the economy parking site is full and the business parking site is not full. Case three is that the economy parking site is not full and the business parking site is full. Case four is that both the economy parking site and the business parking site are full. We use $(i = [1, 2, 3, 4])$ to denote these 4 cases. In the following discussion, we will use these notations:

- k_1 is the number of slots which are filled at time t in the economy parking site.
- k_2 is the number of slots are filled at time t in the business parking site.
- N_1 is the fixed number of the economy parking slots.
- N_2 is the fixed number of the business parking slots.
- $p_i(s_1)$, $(i = [1, 2, 3, 4])$ is the probability that case i happens in the economy parking site (we use s_1 to denote the economy parking site).
- $p_i(s_2)$, $(i = [1, 2, 3, 4])$ is the probability that case i happens in the economy parking site (we use s_2 to denote the business parking site)
- r_i, $(i = [1, 2, 3, 4])$ is the average revenue that the case i can obtain.
- R is the total average revenue that the whole parking site can obtain.
- f_1 is the fee to park in the economy parking site.
- f_2 is the fee to park in the business parking site.

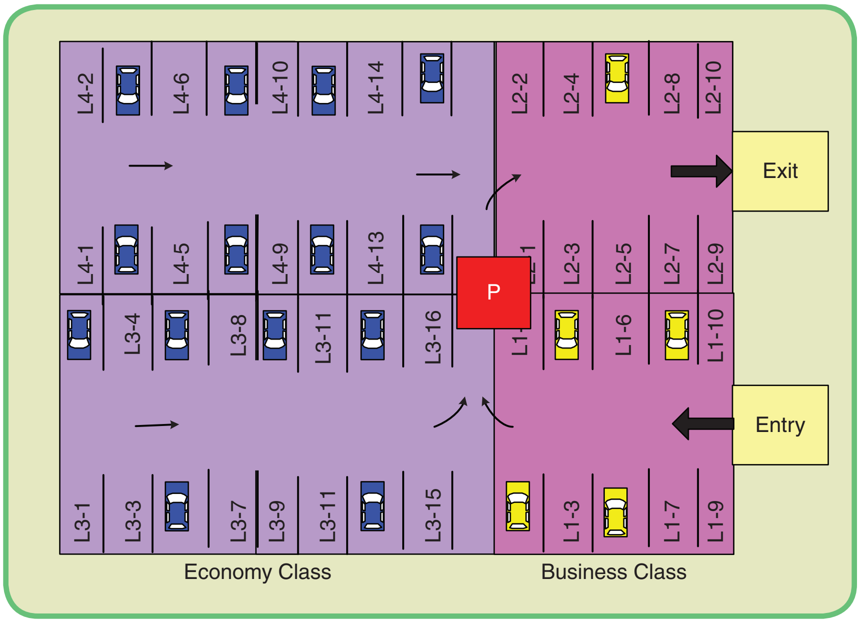


FIG 6 Parking class.

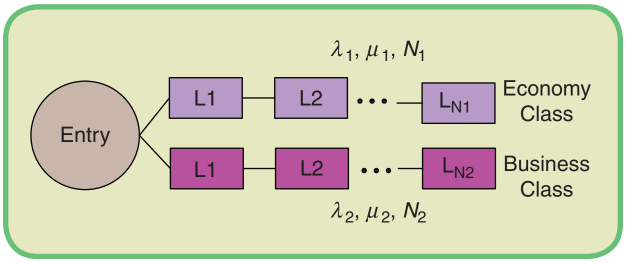


FIG 7 Parking class chain.

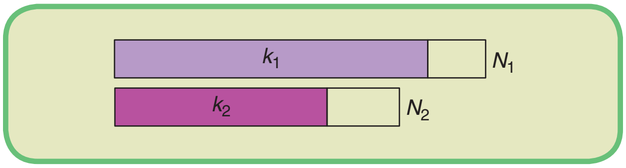


FIG 8 S_1 and S_2 are not full.

1) Case 1: none of s_1,s_2 are full

The number of busy slots is less than the number of the total parking capacity in both the economy parking site and the business parking site. In this scenario, none of s_1, s_2 are full, i.e., $k_1 < N_1$ and $k_2 < N_2$, as shown in Fig. 8.

Therefore, the probability of $k_1 < N_1$ is

$$p_1(s_1) = \sum_{k=0}^{N_1-1} p_k(t) \tag{5}$$

the probability of $k_2 < N_2$ is

$$p_1(s_2) = \sum_{k=0}^{N_2-1} p_k(t) \tag{6}$$

$$r_1 = p_1(s_1) \times p_1(s_2) \times (p_1 k_1 f_1 + p_2 k_2 f_2) \tag{7}$$

The production of $p_1(s_1) \times p_1(s_2)$ is the probability that case 1 happens. The summation of $p_1 k_1 f_1 + p_2 k_2 f_2$ is the revenue that case one can obtain. Therefore the r_1 is the mean revenue that case one can obtain.

2) Case 2: s_1 is full and s_2 is not full

In this scenario, s_1 is full and s_2 is not full, i.e., $N_1 + N_2 - k_2 \geq k_1 > N_1$ and $k_2 < N_2$.

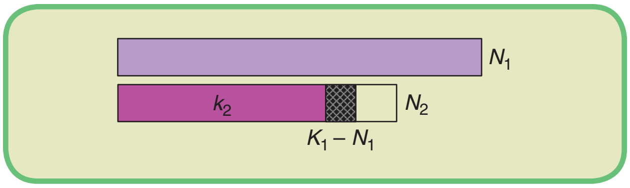


FIG 9 S_1 is full and S_2 is not full.

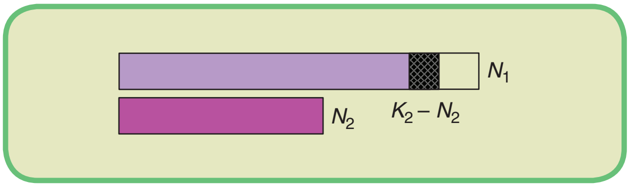


FIG 10 S_1 is not full and S_2 is full.

The probability of $N_1 + N_2 - k_2 \geq k_1 > N_1$ is

$$p_2(s_1) = \sum_{k=N_1}^{N_1+N_2-k_2} p_k(t) \tag{8}$$

the probability of $k_2 < N_2$ is

$$p_2(s_2) = \sum_{k=0}^{N_2-1} p_k(t) \tag{9}$$

$$r_2 = p_2(s_1) \times p_2(s_2) \times [p_1 N_1 f_1 + p_1(k_1 - N_1) f_1 + p_2 k_2 f_2] \tag{10}$$

3) Case 3: s_1 is not full and s_2 is full

In this scenario, s_1 is not full and s_2 is full, i.e., $k_1 < N_1$ and $N_1 + N_2 - k_1 \geq k_2 > N_2$.

The probability of $k_1 < N_1$ is

$$p_3(s_1) = \sum_{k=0}^{N_1-1} p_k(t) \tag{11}$$

the probability of $N_1 + N_2 - k_1 \geq k_2 > N_2$ is

$$p_3(s_2) = \sum_{k=N_2}^{N_1+N_2-k_1} p_k(t) \tag{12}$$

$$r_3 = p_3(s_1) \times p_3(s_2) \times [p_1 k_1 f_1 + p_2(k_2 - N_2) f_1 + p_2 N_2 f_2] \tag{13}$$

4) Case 4: both s_1 s_2 are full

In this scenario, s_1 is full and s_2 is full, i.e., $k_1 = N_1$ and $k_2 = N_2$.

The probability of $k_1 = N_1$ is

$$p_4(s_1) = p_{N_1}(t) \tag{14}$$

the probability of $k_2 = N_2$ is

$$p_4(s_2) = p_{N_2}(t) \tag{15}$$

$$r_4 = p_3(s_1) \times p_3(s_2) \times (p_1 N_1 f_1 + p_2 N_2 f_2) \tag{16}$$

C. Expected Total Revenue

$$R = p_{r_1} r_1 + p_{r_2} r_2 + p_{r_3} r_3 + p_{r_4} r_4 \tag{17}$$

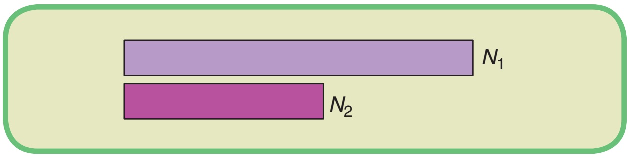


FIG 11 S_1 and S_2 are full.

V. Parking Maintenance

The parking maintenance work includes the routine check on electronics, clearance of misparked vehicles, etc. In the systematic perspective maintenance is also integral part of the parking service. The investor of the parking site can be pleased to know when the parking system can be well-maintained. If the maintenance work is too often it will interrupt the parking service. If the maintenance work is too seldom the parking service may stay malfunctioning. In this section we will address the optimal maintenance time, i.e., the expected time we have to wait before the maintenance work can start.

Suppose the vehicles arrival rate to the parking site is λ. Before maintaining the parking lot, we wait until we find no vehicles will come in next T time units. Of interest is the expected time we have to wait before the maintenance work can start.

Assume we start to count vehicles at time 0 and let $X_1, X_2, \ldots$ the vehicle inter-arrival times. Let, further, W be the random variable that counts the vehicles that will come before we can start the maintenance work. We model this problem as geometric distribution of Bernoulli trials: find the first T which is larger than vehicle inter-arrival time. We write

$$\begin{aligned} Pr[\{W = k\}] &= Pr[\{X_1 < T\} \cap \{X_2 < T\} \cap \ \ldots \ \cap \{X_k < T\} \\ &\quad \cap \{X_{k+1} \geq T\}] \\ &= Pr[\{X_1 < T\}] \cdot Pr[\{X_2 < T\}] \cdot \ \ldots \ \cdot Pr[\{X_k < T\}] \\ &\quad \cdot Pr[\{X_{k+1} \geq T\}] \\ &= (1 - e^{-\lambda T})^k e^{-\lambda T} \end{aligned}$$

Thus, the expected number of vehicles that come before we can start maintenance is

$$\begin{aligned} E[W] &= \sum_{k \geq 0} k(1 - e^{-\lambda T})^k e^{-\lambda T} \\ &= (1 - e^{-\lambda T}) e^{-\lambda T} \sum_{k \geq 0} k(1 - e^{-\lambda T})^{k-1} \\ &= (1 - e^{-\lambda T}) e^{-\lambda T} e^{2\lambda T} \\ &= e^{-\lambda T} - 1 \end{aligned}$$

Finally, the expected time that we have to wait until we can start maintenance work is

$$E[W]E[X] = \frac{e^{-\lambda T} - 1}{\lambda}. \tag{18}$$

VI. Simulation Results

In this section, we present both numerical and simulation results of the proposed techniques. We focus on the critical parameters of parking services. Implementation and simulation of the complete parameters of the parking services remains for future work. Numerical results were generated using MATLAB 7.0 and our customized simulator. Simulation results were collected and processed using custom simulators for the various parking service. The simulation development was done in Visual Studio.NET and Eclipse. Please refer to table in Appendix for a reminder of the variables used in the simulations.

A. Comparison to Conventional Parking

In the simulation, we compare two scenarios. In scenario one representing conventional parking system, drivers randomly select a parking spot. The parking spot is based on first-come-first-serve. The process that drivers arrive at or exit to the parking lot is a Poisson Process. If they move around the parking area and can not find a parking spot, they turn around. If they turn around 3 times, they exit. In scenario two representing the proposed intelligent parking system, drivers reserve a parking spot. The process that drivers arrive at or exit to the parking lot is the same Poisson Process. There are two types of parking areas. One is the economy class area and the other is the business class area. We assume 1% of drivers will disobey the reservation and take somebody else's parking spot for their own convenience. The remaining 99% of drivers obey the reservation. We compare the parking utilization and average waiting time for drivers. The parking capacity is 2000 parking spots. The average arrival rate is 0.5 vehicle/min [16]. The simulation parameters and values are listed in Table I.

First, we evaluated the utilization of parking spots. We varied the capacity of parking lot from 100 spots to 2800 spots. For each day, we simulated 8 hours because we want to simulate daytime parking. An average parking utilization rate is obtained by calculating 7 days' average parking utilization rate. As we expected, the conventional parking approach has less parking spot utilization than our proposed SmartParking, as shown in Fig. 12.

We are interested in how much time a driver uses to search for an empty parking spot inside a parking area. Again we varied the capacity of parking spaces from 100 spots to 2800 spots. We calculated 7 days' average search time. The search time starts from entry time to the time when an empty parking spot is found. Our proposed SmartParking almost keeps the same amount of time, as we expected, shown in Fig. 13. Drivers will receive the location and direction to the parking spot and they can directly drive to the parking spot without searching. But the conventional parking approach takes more search time as the parking capacity increases. The searching time will sharply increase when the

Table I. Parameters and values.

Exit booth service rate	5 vehicles/min
Entry booth service rate	20 vehicles/min
Number of exit booths	5
Number of entry booths	1
Average arrival rate	0.5 vehicle/min
Average exit rate	0.5 vehicle/min
Average parking time	1.5 hour

Appendix

$X(t)$	the number of slots in use at time t
h	an epoch of time when only one more slot is in use
$p_i(t)$	the probability that the number of parking cars is i at time t
$o(h)$	a higher-order infinitesimal as $h \to 0$
μ	death rate (car leaving rate)
λ	birth rate (car entering rate)
μ_1	death rate in economy class
λ_1	birth rate in economy class
μ_2	death rate in business class
λ_2	birth rate in business class
i_0	the number of parking cars, at $t = 0$
$g(t, u)$	generating functions regarding t and μ
p	probability parameter in Binomial distribution
$\Lambda(t)$	Poison distribution
$E\{X(t)\}$	expectation of variable $X(t)$
$X_0(t)$	Binomial distribution
$X_1(t)$	Poison distribution
N_1	the capacity of economy class slots
N_1	the capacity of business class slots
k_1	the number of slots are filled at time t in the economy parking site
k_2	the number of slots are filled at time t in the business parking site
s_1	the economy slots
s_2	the business slots
f_1	the parking fee in economy class
f_2	the parking fee in business class
R	the total revenue of the parking site

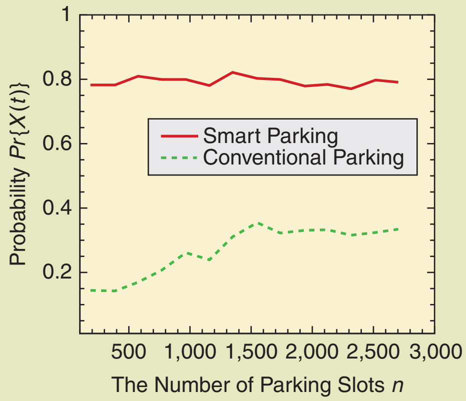


FIG 12 Parking utilization.

parking slot becomes big (the total number of parking spots increases). The bigger parking slot will cause longer searching time because each individual search will take longer time.

B. Probability and Mean Value Analysis

In this section we will evaluate the probability and the mean value of the number of parked vehicles. The simulation area was of size 5000-units one dimensional array. One unit represents one parking slot. Vehicles arrive according to specified exponential distribution within the simulation area. Each simulation result was based on aggregated results from 1000 independent simulations with the same parameter settings.

The probability density function of the occupied slots is the basis of our analysis. We analyzed and simulated the probability density function (pdf) $P_j(t)$ with respect to several arrival rates and departure rates. Fig. 14 gives simulation results for the pdf $P_j(t)$ corresponding to a series of arrival rates and departure rates, given the capacity of parking slots $n = 1000$, and j varies from 0 to 100. 1000 slots are deployed in the environment. We analyzed and simulated in three cases. In case one, λ varies from 1.5 to 3.5, given $\mu = 100$. Fig. 14(a) shows the density function of this case. The increment of μ causes the increment value of the pdf $P_j(t)$. The decrease of arrival rate will cause the same effect. To validate this conclusion, we decrease λ from 150 to 50, remaining $\mu = 2.5$ in second case. Fig. 14(b) shows the simulation results for the second case. As expected, the decrease of the arrival rate causes the increment value of the pdf $P_j(t)$. In case one and case two, we use small values for μ, we use bigger values of μ ranging from 20 to 40. Fig. 14(c) reveals the results of the third case.

In lemma 2, we analyzed the expected value of $X(t)$. Here, we present some results that were derived numerically to analyze $E\{X(t)\}$ in Fig. 15. Again, we simulated in three cases. In case one, we varied the value of λ from 50 to 100, remaining $\mu = 1.5$. Fig 15(a) gives increment value of $E\{X(t)\}$. The simulation results match with the theory result. The results make sense because the increment of the entry rate will increase the number of parked vehicles. In the second case, we varied μ from 1.5 to 2.5, remaining $\lambda = 100$. Fig. 15(b) shows the increment of μ causes the decreasing value of $E\{X(t)\}$. The simulation results match with the theory result. The results make sense because the increment of exit rate will decrease the number of the parked vehicles. In the third case, we varied μ from 20 to 40, remaining $\lambda = 100$. Fig 15(c) also shows that the expected vehicles has no affected by the entry rate and exit rate. The simulation results match with the theory result. Of interest is the relationship between $E\{X(t)\}$ and $P_j(t)$. Fig. 14 and 15 show the results independently. But the two results match each other. The x-axial value at the peak of $P_j(t)$ is equal to the expected value of $X(t)$, i.e. $E\{X(t)\}$. This relationship is somehow similar to the normal distribution.

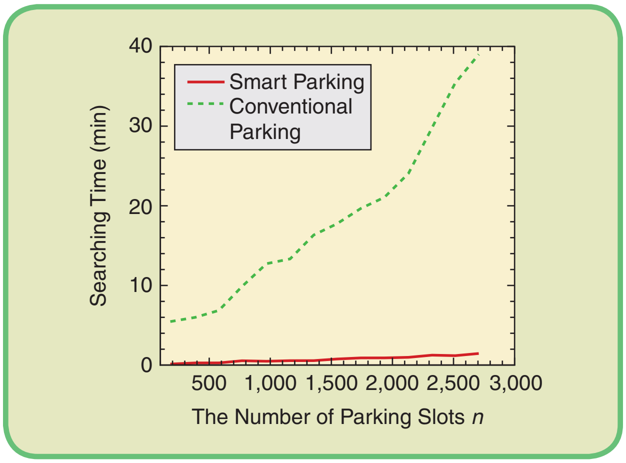


FIG 13 Parking spot searching time.

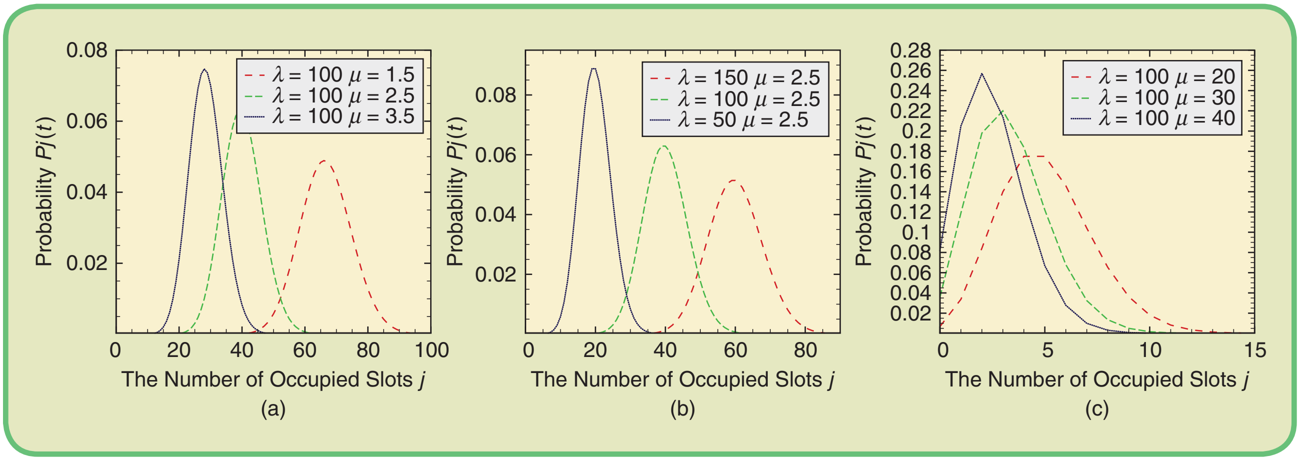


FIG 14 The probability of the number of vehicles $P_j(t)$.

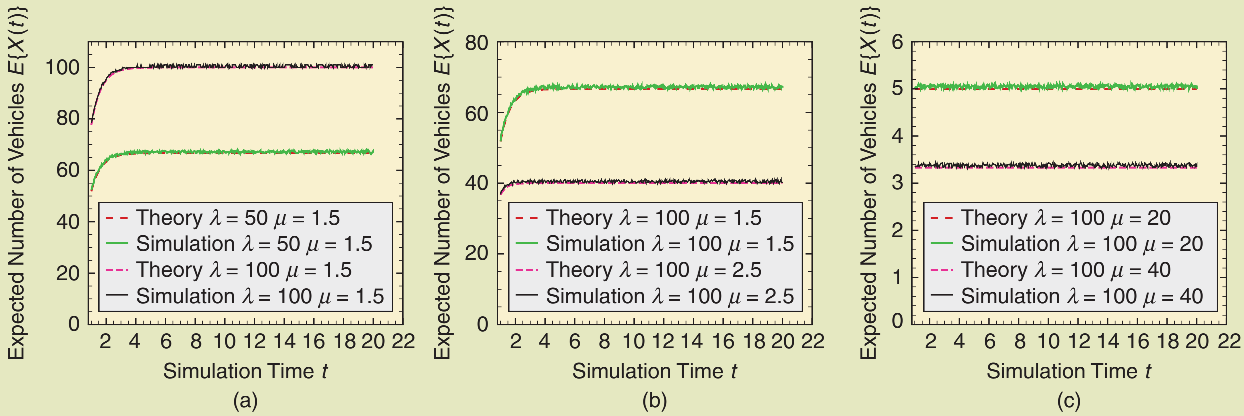


FIG 15 The expected number of occupied slots at time *t*.

C. Average Revenue Analysis

In section B, we presented the analysis of revenue of the proposed parking site. The great advantage of this model is to predict and monitor the average revenue of the parking site. The investor can be pleased with the ability of predicting revenue. In this simulation, we are interested to investigate the relationship between the time and the number of these occupied slots because the revenue is depended on the two variables with a flat parking fee. Fig. 16 shows the occupied slots by simulation time units. The overall occupied slots are consisted of two parts: the business parking slots and the economy parking slots. As expected, the number of occupied slots increases when the simulation time increases. There are more occupied slots in economy class. Therefore, the investor can partition the capacity of economy slots according to this simulation results. A flat fee is charged to each vehicle. For economy parking slots, the flat fee is one unit. For business parking slots, the flat fee is two units. We compared four revenues from homogeneous parking service (which means all the parking slots are same and the parking fee is one unit), the proposed two class parking model, the business parking, and the economy parking. Fig. 17 shows the simulation results. The result matches with the simulation result in Fig 16. The simulation results can guide the investor about the prediction of their revenues.

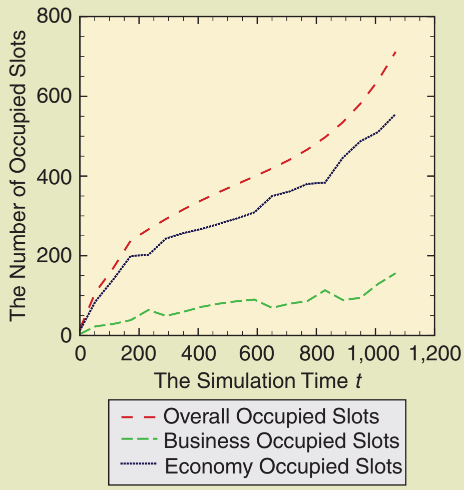


FIG 16 The number of occupied slots.

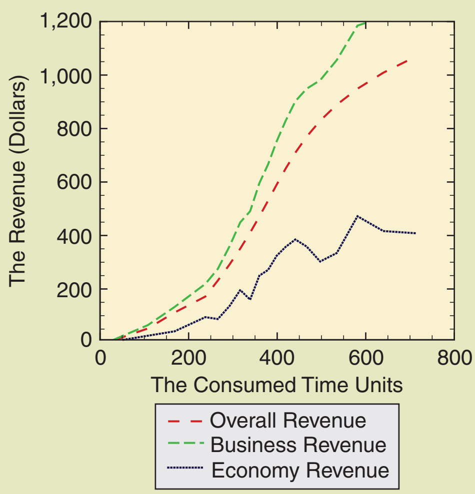


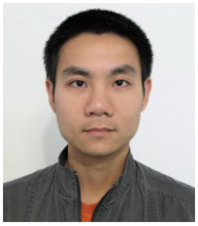
FIG 17 The average parking site revenue.

VII. Conclusions and Future Work

This paper has proposed a smart parking system. By using the secured wireless network and sensor communication, SmartParking is a intelligent parking service application as well as a novel security/privacy aware infrastructure. First, vehicles on the road can view and reserve a parking spot. The parking process can be an efficient and non-stop service. On the other hand, parking service is an intelligent service. New vacant parking spot and advertisement of discount of parking fees can be distributed to the cars passing by. Second, the parking process has been modeled as a stochastic process. Not only maintenance work can be scheduled but also the revenue of the parking site can be predict. New business promotions can be broadcasted to all vehicles passing by the parking site through wireless networks. Finally, privacy of the drivers and security of the information are protected by using the sensor infrastructure and encryption/decryption approach. Simulation results prove the proposed system results in high parking space utilization and fast parking spot finding time. The future work includes more extensive simulations on the proposal. The analysis of efficiency needs to be studied as well.

About the Authors

Gongjun Yan received his Ph.D. in Computer Science from Old Dominion University and currently is an Assistant Professor in Informatics in Indiana University. He applied mathematics models and computer simulations to analyze research problems in information security, Vehicular Ad Hoc Networks, and Wireless Communications.

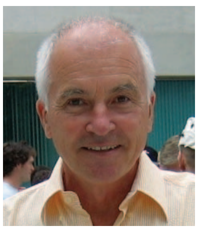


Weiming Yang (second author) College of Mathematics and Statistics, Chongqing Technology and Business University ywmls@hotmail.com

Weiming Yang is a researcher and instructor at College of Mathematics and Statistics of Chongqing Technology and Business University. He got his first master's degree in Applied Mathematics from the University of Toledo, and second master's degree and Ph.D. of Statistics from Old Dominion University. His research area involves longitudinal data analysis, time series and copula models.

Danda B. Rawat (third author) Department of Electrical and Computer Engineering, Old Dominion University drawa001@odu.edu

Danda B. Rawat received his Ph.D. in Electrical and Computer Engineering from Old Dominion University in 2010. His research interests include design, analysis, and evaluation of wireless systems, cognitive radio networks, vehicular ad-hoc networks, wireless sensor networks, Wireless LAN, wireless network security, embedded systems, and smart grid.



Stephan Olariu (fourth author) Department of Computer Science, Old Dominion University olariu@cs.odu.edu

Professor Olariu has held many different roles and responsibilities as a member of numerous organizations and teams. Much of his experience has been with the design and implementation of robust protocols for wireless networks and in particular sensor networks and their applications. Professor Olariu is applying mathematical modeling and analytical frameworks to the resolution of problems ranging from securing communications, to predicting the behavior of complex systems, to evaluating performance of wireless networks. His research interests are in the area of complex intelligent systems enabled by large-scale deployments of sensors and actors and more specifically in securing systems of systems.

Professor Olariu is an Associate Editor-in-Chief of *IEEE Transactions on Parallel and Distributed Systems* and serves on the editorial board of *IEEE Transactions on Computers, Networks, Journal of Parallel and Distributed Computing, Journal of Ad hoc and Sensor Networks, and Parallel, Emergent and Distributed Systems*.

References

[1] NYCDCP, "North America CBD Parking Rate Survey Highlights, New York City Department of City Planning," in *North America CBD Parking Rate Survey Highlights*, August/September 2006.

[2] M. Caliskan, D. Graupner, and M. Mauve, "Decentralized discovery of free parking places," in *VANET '06: Proceedings of the 3rd international workshop on Vehicular ad hoc networks,* New York, NY, USA, 2006, pp. 30–39.

[3] L. E. Y. Mimbela and L. A. Klein, "A summary of vehicle detection and surveillance technologies used in intelligent transportation systems," Nov. 2000.

[4] J. Wolff, T. Heuer, H. Gao, M. Weinmann, S. Voit, and U. Hartmann, "Parking monitor system based on magnetic field sensors," in *Proceedings IEEE Conf. Intelligent Transportation Systems*, Toronto, CA, 2006, pp. 1275–1279.

[5] V. Tang, Y. Zheng, and J. Cao, "An intelligent car park management system based on wireless sensor networks," in *Proceedings Int. Sym. Pervasive Computing and Applications,* Urumqi, 2006, pp. 65–70.

[6] C. Stiller and J. Gayko, "Kognitive automobile," *Automatisierungstechnik*, vol. 56, no. 11, pp. 551 553, 2008.

[7] J. P. Benson, T. O Donovan, P. O Sullivan, U. Roedig, and C. Sreenan, "Car-park management using wireless sensor networks," in *Proceedings of 31st IEEE Conf. Local Computer Networks,* Tampa, 2006, pp. 588–595.

[8] H. Takizawa, K. Yamada, and T. Ito, "Vehicles detection using sensor fusion," in *Proceedings of International Symposium on Intelligent Vehicles (IVS04)*, Parma, Italy, 2004, pp. 238–243.

[9] Z. F. Zhu, Y. Zhao, and H. Q. Lu, "Sequential architecture for efficient car detection," in *Proceedings of IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 2007)*, Minneapolis, 2007, pp. 1–8.

[10] S. Funck, N. Mohler, and W. Oertel, "Determining car-park occupancy from single images," in *Proceedings of International Symposium on Intelligent Vehicles (IVS04)*, Parma, Italy, 2004, pp. 325–328.

[11] R. Panayappan, J. M. Trivedi, A. Studer, and A. Perrig, "Vanet-based approach for parking space availability," in *VANET '07: Proceedings of the fourth ACM international workshop on Vehicular ad hoc networks*, New York, NY, USA, 2007, pp. 75–76.

[12] G. Yan, S. Olariu, M. C. Weigle, and M. Abuelela, "Smartparking: A secure and intelligent parking system using NOTICE," in *Proceedings of the International IEEE Conference on Intelligent Transportation Systems*, Beijing, China, Oct. 2008, pp. 569–574.

[13] R. L. L. Jia, "On the layout of fixed urban traffic detectors: an application study," *IEEE Intelligent Transportation Systems Magazine*, vol. 1, no. 2, pp. 6–12.

[14] R. Huijing Zhao Jinshi Cui Hongbin Zha Katabira, K. Xiaowei Shao Shibasaki, "Sensing an intersection using a network of laser scanners and video cameras," *IEEE Intelligent Transportation Systems Magazine*, vol. 1, no. 2, pp. 31–37.

[15] G. Yan, S. Olariu, and M. C. Weigle, "Cross-layer location verification enhancement in vehicular networks," in *Proceedings of the IEEE Intelligent Vehicles Symposium*, San Diego, USA, Jun. 2010, pp. 95–100.

[16] Y. Asakura and M. Kashiwadani, "Effects of parking availability information on system performance: a simulation model approach," in *Proceedings of Vehicle Navigation and Information Systems Conference*, Dearborn, MI, Aug. 1994, pp. 251–254.