Smart Parking:

Guidance, Monitoring and Reservations

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This dissertation is submitted for the degree of

Doctor of Philosophy

September 2016

to my beloved parents …

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification at this, or any other university. This dissertation is my own work and contains no content which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgments.

Amir O. Kotb
September 2016

Acknowledgements

During my PhD study in the Department of Electrical Engineering and Electronics at the University of Liverpool, I am honored and privileged to have met so many incredible people who have given me assistance and motivation along the way.

First and foremost, I would like to express my profound appreciation to my PhD supervisors, Dr. Yaochun Shen and Prof. Yi Huang, for their constant support and motivational guidance. Their enthusiasm for research, thorough work ethics and remarkable leadership had always motivated me. They taught me how to express one's research ideas in a structured, clear and motivational way. I feel very privileged and honored to have worked with them.

A special thanks to Dr. Xu Zhu and Dr. Harm Van Zalinge - my annual progress assessors - for taking their precious time and giving invaluable comments on my work. Many thanks for Dr. Xu who co-authored two of my journal papers - my thesis could not be at this level without her advice. Special thanks also goes to Prof. Simon Maskell for his important advice and guidance.

I would like to thank all my friends and colleagues in the High Frequency Research Group: Sheng Yuan, Qian Xu, Lei Xing, Muayad Kod, Saqer Al Jaafreh, Rula Alrawashdeh, Abed Sohrab, Zhe Xi, Chaoyun Song and Tian Zhihao. Being part of this group is a joy as well as a great place for having valuable advice and collaboration. I am thankful to all those who made my PhD study a pleasurable journey: Mohammed Heggo, Mohammed Saadeh, Waleed Al Sit, Hamza Al Zu'bi, Mohammed Al Sumairi, Qussay Al Jubouri and many others. Special thanks goes to Hannah Fosh, Jill Anson, Jane Galagher and Jane Bainbridge.

Finally, I would like to give my deepest gratitude to my family. I owe a lot to my parents Osama Kotb and Naglaa Hassan for bringing me up and raising me, for supporting and standing by me in all times without waiting a reward. Thanks goes to my sisters Amira and Dahab for their love and constant good wishes. Thanks should also go to my brothers in law, Hossam Ghorayeb and Tamer Salah. I am also sincerely thankful to my better half, my dear wife, Mirhane Salah, for her love, support, help, and encouragement. My regret and apology to my kids, Adam and Eline, for not spending enough time with them during this journey.

Abstract

Today, parking is the main coordinator between the land use and transportation. As the urban population is increasing, more and more cars are circulating through the city in search for parking spaces, often contributing to the global problem of traffic congestion. Hence, several governments seek to improve their existing transportation systems and infrastructure. Examples of their initiatives include the launch of ‘Smart Parking’ projects in major urban areas. However, the developments to date in this area have some significant limitations lodged against them. In this dissertation, we propose 3 different smart parking systems: iParker, INDO and RFPark, to enhance the overall parking scheme.

First, iParker and INDO are introduced as new parking management and reservations systems. Both change the parking behaviour from driver-side parking searching to system-side allocation. This is achieved by solving new Mixed Integer Linear Programming (MILP) optimisation problems with the objective of minimising driver’s cost functions, while ensuring the maximum parking resource utilisation. Nevertheless, there are several differences between iParker and INDO.

iParker is designed to operate as a country-wide scaled system to offer drivers the optimal parking lot allocation and reservation before or at arrival to their destinations. This is based on minimising a driver’s cost function that combines parking cost, reservation fees, proximity to multiple destinations and reservation type. As opposed to current reservation systems, iParker offers both static long-term reservations and dynamic short-term reservations, for both on-street and off-street parking lots. In addition, new pricing policies are proposed that allow the generation of more parking revenue and the fair distribution of parking traffic across parking lots.

However, INDO is designed to operate inside individual parking lots who serve giant buildings - such as shopping malls - to offer the drivers the immediate optimal parking space allocation and the indoor guidance. A driver's cost function here combines the times of driving inside the parking lot and walking inside the indoor destination. In addition, a Radio Frequency Identification/Near Field Communication (RFID/NFC) based navigation component is developed to provide commuters with guidance and navigation in the car park and the indoor destination.

Based on simulation results, compared to the non-guided or the state-of-the-art guidance-based systems, iParker and INDO significantly reduce the average time to find a parking space and the drivers' cost, while the parking resources are more efficiently utilised. The pricing policies of iParker lead to the generation of more revenue and fair balance of traffic load across parking lots. In addition, INDO substantially reduces the commuting time indoors.

On the other hand, RFPark is proposed as a new approach to parking monitoring. For the first time, Ultra High Frequency (UHF) passive RFID tags are deployed on the asphalt, and interrogated by RFID reader antennas above the parking spaces to detect the occupancy states. Most of the problems of the current cutting-edge parking occupancy detection systems are not present in this system. RFPark was analysed and implemented to show a pilot study in a real world outdoor parking environment in the University of Liverpool and has proved to have a very high detection accuracy.

The innovative design and development of these 3 systems form a new 'Smart Parking' solution that offers to reduce the parking-related traffic congestion, enhance driver experience and improve the overall parking scheme. Although there are some challenges regarding the realisation of these smart systems, they are addressed here and solutions to them are proposed in this dissertation.

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Acronyms

AOA	Angle of Arrival
COO	Cell of Origin
CS	Central Server
EPC	Electronic Product Code
G	Guided System
GIS	Geographic Information System
GPS	Global Positioning System
GUI	Graphical User Interface
HF	High Frequency
HTTP	Hypertext Transfer Protocol
ING	Indoor Navigation and Guidance
INS	Inertial Sensors
ITS	Intelligent Transportation Systems
LF	Low Frequency
NFC	Near Field Communication

NG	Non-Guided System
PM	Parking Manager
POI	Point of Interest
PRS	Parking Reservation System
RFID	Radio Frequency Identification
RTU	Remote Terminal Unit
SAS	Smart Allocation System
SC	Smart Commuting
SP	Smart Parking
TOA	Time of Arrival
UHF	Ultra High Frequency
VICS	Vehicle Information Communication System
VMS	Variable Message Sign
MILP	Mixed Integer Linear Programming
PGI	Parking Guidance and Information

Chapter 1

Introduction

1.1 Motivations

In recent years, transport has increasingly become an important economical, environmental and political issue. As the urban population is growing, denser urban mobility is brought about and several transportation problems arise. The fundamental concern realised by both governments and people is with regards to the desperate need to ease the traffic congestion.

There is a growing body of evidence that states that searching for parking is a major leading cause of congestion, and there are many valid reasons for this. For instance, it has been reported that vehicles searching for parking spaces contribute to as much as 30% of city traffic in large urban areas [1]. On a daily basis, each vehicle on the road wastes 8-20 minutes cruising for a vacant parking spot [1], [2]. This causes not only a loss of time, money and effort for the drivers looking for parking, it also contributes to an extra loss of time, money and effort for other drivers as a result of traffic congestion [3]. A study by the Texas Transportation Institute's 2015 Urban Mobility Report reveals that in 2014, congestion caused urban Americans to drive an extra 6.9 billion hours and buy an extra 3.1 billion gallons of fuel which represented an economic loss of over $160 billion, an increase of over 105% from

2005 [4]. The recognition of the global and local impact in light of these statistics emphasises the significance of the problem that this dissertation seeks to address.

In response to these environmental challenges as well as economic opportunities, numerous countries seek to improve and manage their existing transportation systems and road infrastructure to enhance traffic flow, mobility and safety [5]. One example of such a response is the building and deployment of guidance-based systems, such as Parking Guidance and Information (PGI) systems, for a better parking management. PGI systems provide the drivers with dynamic information within controlled areas about the availability of parking spaces and directions to them. Data about the vacancy of parking spaces are extracted from sensors deployed on or off the roadway, then they are conveyed to the drivers through Virtual Message Signs (VMS) on the road or through the internet [6, 7]. PGI systems are a product of the global initiative of Intelligent Transportation Systems (ITS) in urban areas. They are designed with the objective of minimising the parking search time which in turn reduces traffic congestion.

Concurrently, a considerable amount of research has been conducted in the area of Parking Reservation Systems (PRS) which allows the commuters to obtain parking information before or during their journey, and obtain guaranteed parking reservations at their desired destinations [8]. PRS usually integrate PGI systems for the parking spaces monitoring component. The reservations component, which is usually an online service accessed by the internet, phone or Short Message Service (SMS), is responsible of receiving reservations requests and effectively offering parking reservations that match the drivers' needs. The reservations offers can be generated based on Parking Space Optimisation Service (PSOS) which is usually designed to maximise the parking resource utilisation, minimise the drivers' cost or both. PRS promise to reduce parking search time, provide dynamic parking information, guarantee parking at a journey destination, facilitate parking payment, improve drivers' parking experience, improve parking spaces management, maximise parking resources utilisation and increase total revenues.

PGI systems and PRS are two examples of innovative initiatives to ease traffic congestion caused by the parking search, though there are other numerous approaches to tackle the same problem, such as Transit-based Parking, Automated Parking, and the utilisation of different parking pricing policies, e.g. dynamic pricing. Good though all this is, this dissertation offers to alleviate some significant limitations (see Chapter 2) lodged against the developments to date in this area of work. The solution presented here offers smarter parking guidance, management, monitoring and reservations and is broken down into 3 different systems - as shown in Fig. 1.1.

1.2 Contributions

The main contributions of this dissertation are as follows.

- We propose a novel "Smart Parking" system named iParker that is based on dynamic resource allocation, reservations and pricing. This system basically changes the conventional parking behaviour from driver-side parking searching and competition to system-side allocation. The majority of the parking issues in the present state-of-the-art guidance-based parking systems can be alleviated in our new system framework. Our system is designed to be implemented on a large scale, e.g., countrywide and it incorporates parking wireless sensor network, reservations control engine, pricing control and smart parking services.

- We propose a novel algorithm that is formulated as a Mixed Integer Linear Programming (MILP) problem to solve the parking resource allocation problem for iParker. Optimal allocation is obtained as a solution for each MILP based on current drivers and system state information and subject to random

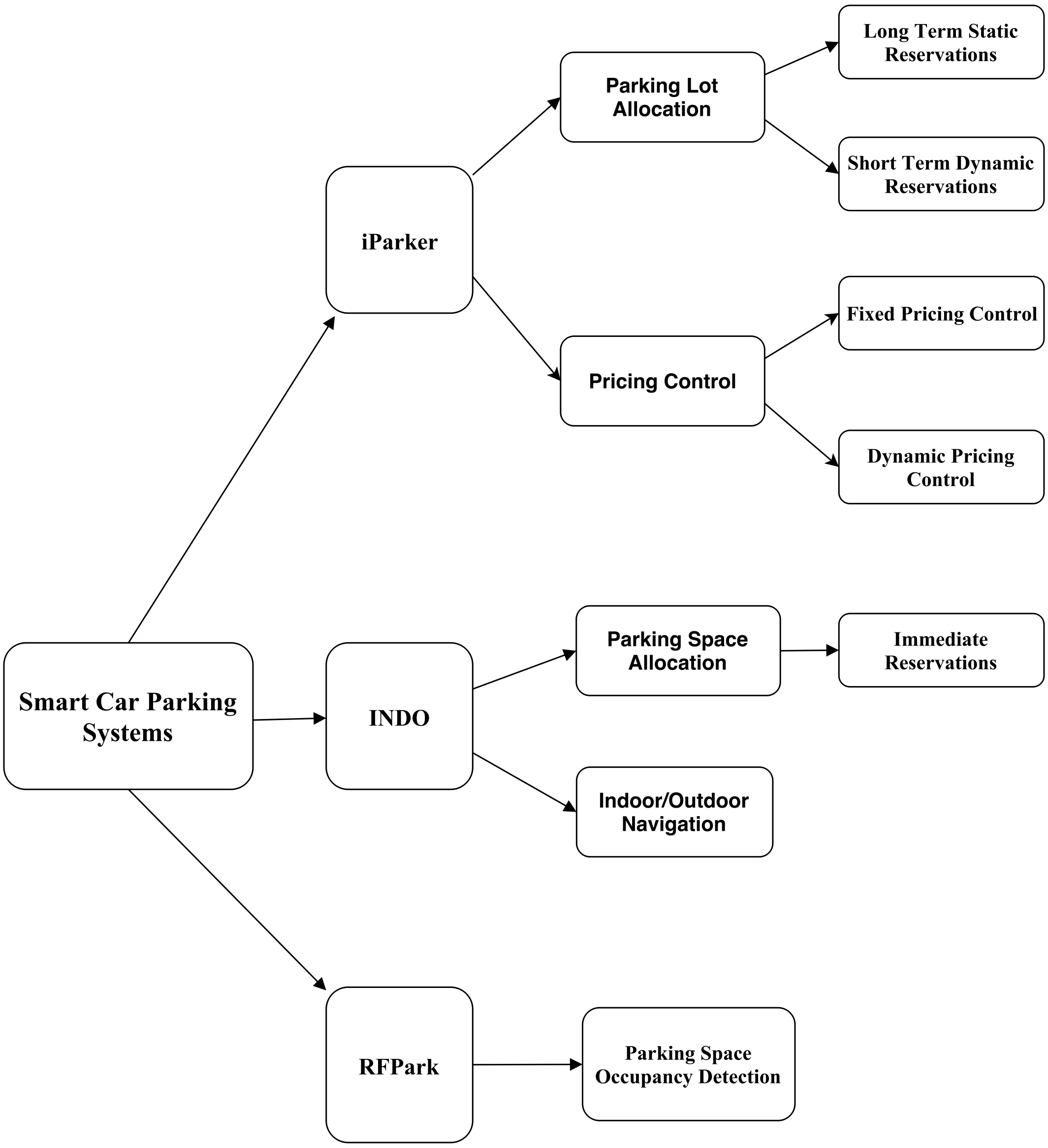


Figure 1.1: A descriptive graph of the proposed smart car parking systems.

events, e.g., driver requests or parking sensors update. Our model allows short-term dynamic reservations (few minutes/hours ahead reservations, unbounded arrival-departure times and continuously allocating better parking resource until the driver reaches the destination) and long-term static reservations (many hours/days ahead reservations, bounded arrival-departure times, static reservations) with the objective of minimising the drivers' cost function and maximising the parking resource utilisation. The allocation ensures no reservation conflict, and that a set of fairness constraints are satisfied. Great improvements over unguided and guided-based systems are shown in the simulation results.

- We propose a new pricing policy that sets the fee for parking reservations for both short-term and long-term reservations. Simulation results indicate a significant increase in the parking revenue as well as an increased total parking resource utilisation. In addition, an algorithm for dynamic pricing control that balances the traffic flow, parking utilisation and revenue across parking lots (on-street and off-street) is proposed.

- We also propose a novel "Smart Commuting and Parking" system named INDO that is based on Radio Frequency Identification/Near Field Communications (RFID/NFC), Resource Allocation and Navigation. This system utilises the information about indoor building and car park digital maps to allocate and reserve the optimal parking spaces nearest drivers' indoor destinations. In addition, a Cell-of-Origin-based indoor navigation is incorporated using RFID/NFC to allow the users navigate from parking space to destination and vice versa. INDO can be integrated into our bigger system iParker as it is designed to be implemented on the smaller scale, e.g., shopping mall. The system can also incorporate new technologies, such as digital advertising, marketing, etc..

- We propose another novel algorithm that is formulated as a MILP problem to solve the parking resource allocation problem for INDO. The optimal parking space, entrance and exit gates (for parking lot and indoor building) are the result of each MILP and are obtained by utilising Dijkstra shortest path algorithm. We also modeled the parking and commuting behaviours in the unguided and guided scenarios and compared them to our model. Simulation results show a significant reduction in the average commuting time for all users as well as an increase in the parking areas capacity during the times of heavy traffic.

- We design and develop a software package for indoor navigation, including an application for Android smart phones that utilises RFID/NFC technology, our own mapping software that creates digital maps and a server application. This software package is the implementation of the indoor navigation sub-system of INDO.

- We propose a new parking spot occupancy detection system using passive Ultra High Frequency (UHF) RFID, named RFPark. This system can be categorised in the state-of-art Parking Guidance and Information Systems (PGI), in which passive RFID tags are placed on the asphalt, similar to on-roadway sensors of PGI, and interrogated by RFID antennas above the parking spaces to detect the occupancy states. Most of the problems in the current cutting-edge parking occupancy detection systems - sensitivity to weather conditions, complex installation, expensive maintenance, etc. - are not present in our system.

- We also design and implement RFPark system in some of the parking spaces of the University of Liverpool. We use RFID equipment and develop our own web server, mapping software and Windows and smart phone applications.

1.3 Outline of the Thesis

This thesis is organized as follows.

Chapter 2 presents the background about the current car parking problems and an overview of the systems and technologies researched and developed with the aim of solving them.

Chapter 3 proposes our novel “Smart Parking” system entitled iParker. We present the overview, architecture and reaction scheme of the proposed system in Section 3.2. The dynamic resource allocation model is described in details and the algorithm is formulated in Section 3.3. Results and discussions are presented in Section 3.4. Finally, Section 3.5 concludes the chapter.

Chapter 4 proposes our novel “Smart Commuting and Parking” system entitled INDO. We present the overview and architecture of the proposed system in Section 4.2. We describe the software and hardware deployment for the indoor navigation sub-system in Section 4.3. The resource allocation model is described and the algorithm is formulated in Section 4.4. Results and discussions are presented in Section 4.5. The implementation and the evaluation of INDO are explained in Section 4.6. Lastly, Section 4.7 concludes the chapter.

Chapter 5 proposes our novel “Parking Spot Occupancy Detection” system entitled RFPark. We present the overview and architecture of the proposed system in Section 5.2. Experimental results of RFID benchmarks on RFID equipment, RFID Reader-Tag Read Range Measurements and overall RFPark performance analysis are discussed in Section 5.3. The implementation and the software algorithm of RFPark are shown in Section 5.4. RFPark realisation challenges are addressed in Section 5.5. Finally, Section 5.6 concludes the chapter.

Chapter 6 presents a summary of the work done in this research, conclusions and further work.

1.4 Publications

Journal Articles

1. A.O. Kotb, Y. Shen, X. Zhu and Y. Huang “iParker - A New Smart Car Parking System Based on Dynamic Resource Allocation and Pricing,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 9, pp. 2637-2647, Sept. 2016.

2. A.O. Kotb, Y. Shen, and Y. Huang “Smart Car Parking Systems: A Review,” *IEEE Intelligent Transportation Systems Magazine*, (Under Review, 2016).

3. A.O. Kotb, X. Zhu, Y. Shen, and Y. Huang “INDO - Smart Indoor Commuting and Car Parking based on RFID/NFC, Resource Allocation and Navigation,” *IEEE Transactions on Vehicular Technology*, (Under Review, 2016).

4. A.O. Kotb, Y. Shen, and Y. Huang “RFPark - A New Smart Car Park Spot Occupancy Detection System Using Passive UHF RFID,” *IEEE Transactions on Intelligent Transportation Systems*, (Under Review, 2016).

Presentations

1. A.O. Kotb, Y. Shen, and Y. Huang. “RFPark - A New Smart Car Park Spot Occupancy Detection System Using Passive UHF RFID,” *International RFID Congress, Marseille, France*, 2015

Chapter 2

Literature Review

2.1 Introduction

Parking could be an expensive process in terms of the money or the time and effort spent. Current studies have revealed that a car is parked for 95 percent of its lifetime and only on the road for the other 5 percent [9]. If we take England in 2014 as an example, on average a car was driven for 361 hours a year according to the British National Travel Survey [10] yielding about 8404 hours in which a car would be parked. Now where would you park your car for these very long hours? Cruising for parking is naturally the first problem caused by the increase of car owners globally. On average, 30 percent of traffic is caused by drivers wandering around for parking spaces [1]. In 2006, a study in France revealed an estimation that 70 million hours were spent every year in France only in searching for parking which resulted in the loss of 700 million Euros annually [11]. In 2011, a global parking survey by IBM [2] stated that 20 minutes are spent on average in searching for a coveted spot. With these statistics, we can predict that a great portion of global pollution and fuel waste is related to cruising for parking [12].

Parking spaces are found to be more than plenty in some places and very rare to find in others. Pricing policies had played an important role in the overall parking availability for decades [13]. Here comes the important question: do we need to have more parking spaces or do we need better parking management?

Numerous countries are working to manage their current transportation systems and road infrastructure to enhance traffic flows, mobility and safety [5]. Emerging from these motivations is the concept of Intelligent Transportation Systems (ITS). ITS are advanced applications applied to transport and infrastructure to exchange information between frameworks for enhanced productivity, safety and environmental performance. ITS vary in technologies applied, from basic management systems; navigation systems, traffic control systems, speed cameras, variable message signs; and to more advanced applications that fuse live information and feedback from other sources, such as Parking Guidance and Information (PGI) systems and Parking Reservation Systems (PRS) [14].

2.2 Parking Guidance and Information Systems (PGI)

In order to solve the parking problem, various types of PGI systems have been developed [15–21]. PGI systems provide the drivers with information about the availability of parking spaces in controlled areas through Virtual Message Signs (VMS) on the road or through the internet [6, 7]. Previous studies, [22–24], show that PGI systems contribute to reducing the overall traffic congestion by assisting the drivers in finding free parking spaces without wasting long times in queuing at car park entrances.

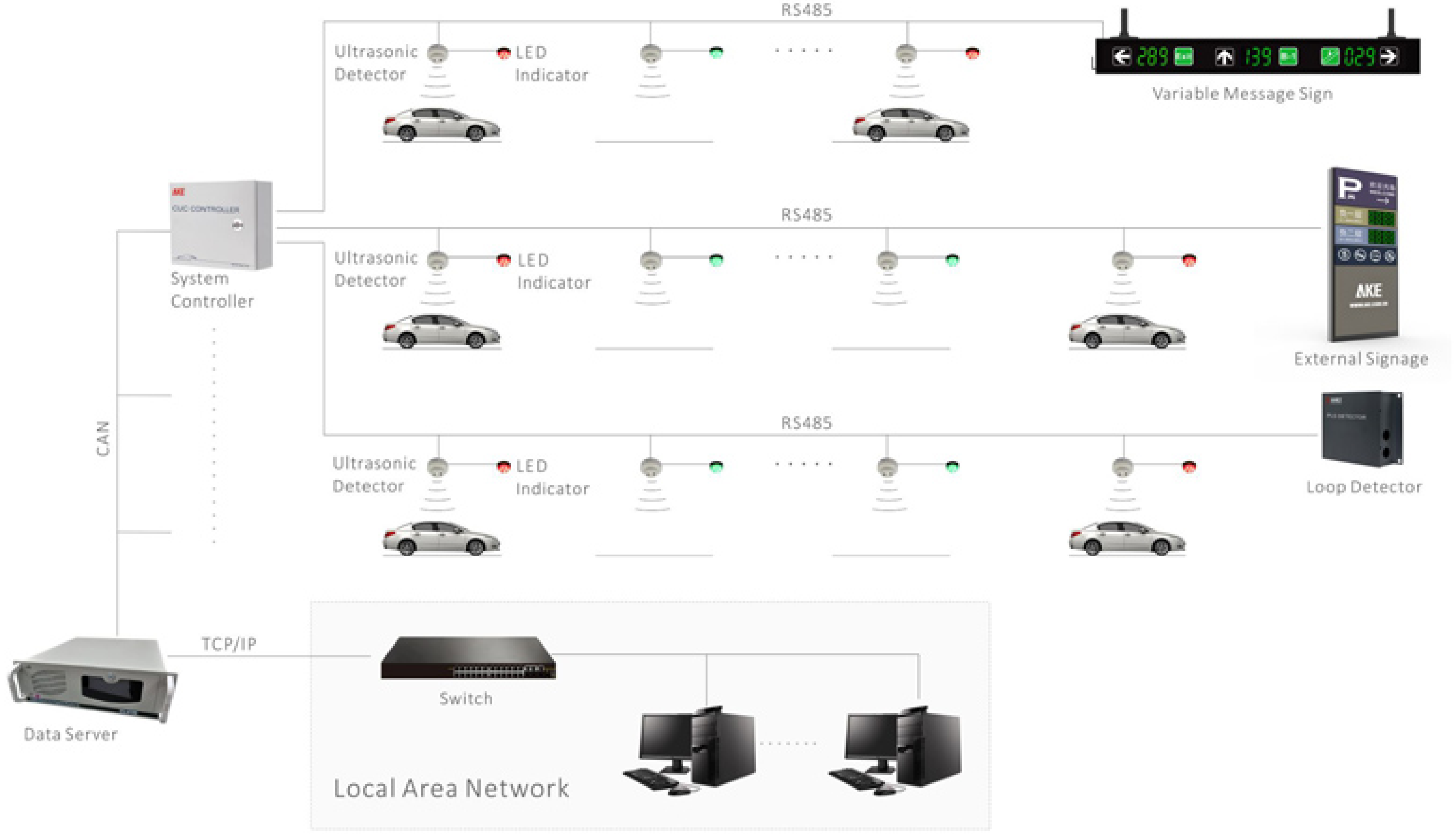


Figure 2.1: Example of a PGI system architecture [25]. Data about the occupancy state is taken from ultrasonic sensors and loop detectors and communicated to a system controller via RS485. The parking information is then published to a local area network by utilising a data server and ip switches.

A PGI system typically consists of 4 main components: parking monitoring mechanism, parking space information dissemination, telecommunications network and control center [26]. Conventional PGI systems typically use barriers and barcode machines to count vehicles entering and exiting the parking area [27]. However, neither the driver nor the parking manager knows the occupancy status of specific parking spots. Whereas some PGI systems utilise sensors or cameras by placing them in the vicinity of the parking area for vehicle detection and surveillance [28]. Fig. 2.1 shows an example architecture of a commercial PGI system.

Sensors for parking space monitoring can be classified as ‘On-Roadway’ or ‘Off-Roadway’ [29]. ‘On-Roadway’ sensors are either tapped to the surface of the roadway or embedded into it; examples are the pneumatic tube, loop detector, magnetic sensor, acoustic sensor, piezoelectric sensor and Radio Frequency Identification (RFID). ‘Off-Roadway’ sensors are placed above the roadway; examples are the ultrasonic sensors, infrared sensor and CCTV cameras. In the following section, we provide an overview on the parking space monitoring sensors.

2.2.1 On-Roadway Sensors

Pneumatic tube: It is an emptied out elastic tube extended over the segment of the roadway where car checks are required. One end of the tube is associated with a pressure sensor and the other end of the tube is obstructed to prevent air leakage as a vehicle goes crosswise over. At the point when a car crosses the tube, the vehicle compresses the tube and raises the air tension inside. The run of the mill tubes are 1.3 mm in distance across. The applied pressure closes an electrical switch that triggers a transmitter that sends the data to a PC, which processes the weight varieties as vehicle counts [30, 31].

Loop detector: It is an inductive loop of wire deployed in a circular or rectangular form - typically into a pre-cut pattern in a lane of the roadway. When an electric current is transmitted through the wire, an electromagnetic field with a quantifiable inductance is generated. when an automobile override the loop, the field will be interrupted and inductance will be reduced. The alter in inductance will be then discovered by a control unit which produces a signal to a processing computer module either in wired or wireless form that by its turn subscribes the inductance variations as vehicle counts [32].

Magnetic sensor: It consists of a sensor coil inside small cylinders that functions in a similar manner to inductive loops. In the presence of a car, the flux density of the sensor increases due to the existence of ferrous materials of the car. In other words, magnetic sensors or magnetometers detect the magnetic anomaly in the Earth magnetic field that results from the presence of a car [33].

There are two types of magnetometers, the Single Axis Magnetometer (SAM) and the Double Axis Magnetometer (DAM). The first is smaller in size, thus can be installed on the ground with minimal disruption to the traffic. However, DAM has much higher detection accuracy as compared to SAM, due to the fact that it uses both the horizontal and the vertical axis to sense the presence of a car. This eliminates the chances of counting a vehicle twice [34].

Acoustic sensor: It relies on the sound energy produced from the interaction between the roadway and vehicle tires. A processing computer analyse the variation in noise levels recognized by microphones and then a signal will be created to advice about car presence [35].

Piezoelectric sensor: It makes use of substance vibration or mechanical stress to generate electrical energy from kinetic energy. The sensor completely depends on how the piezoelectric material is cut and the material itself. The material could be ceramics or crystals [36].

RFID: As described later in this chapter, it consists of a transceiver, transponder and antenna. It consists of a transceiver, transponder and antenna. The transceiver, or in other words, the RFID reader interrogate the transponder/RFID tag to read its unique ID through the RFID reader antenna [37]. To detect the occupancy state of a parking space, RFID reader antennas are placed in the parking area and the RFID tag is placed inside the vehicle. Once a vehicle's tag is read by the RFID reader, the parking space status is changed to occupied [38].

2.2.2 Off-Roadway Sensors

Ultrasonic sensor: It transmits a sound wave in the frequency range of 25-50 kHz and detects the reflected wave from an object - a vehicle in our case. Because of its simplicity and good measurement accuracy, it has been used in many car parking systems to identify the occupancy of parking spaces [39–41].

Infrared sensor: It is either active or passive. Active infrared sensor functions by emitting a narrow beam of IR waves at a defined pulse rate towards the surface of the roadway. A car is detected when some of those waves are reflected back to the sensor and processed to recognize the changes in the characteristics of the IR beam. Passive IR sensor, on the other hand, does not emit energy, it senses the amount of energy emitted during the presence of a car [42].

CCTV: It is an image-based detection technology by utilising CCTV images and applying image processing techniques on the image stream to identify the parking spot occupancy status [43–46]. In a typical system, the digital image stream from a camera is received by a computer. The pictures are then digitized and transferred via a sequence of computer algorithms that recognize changes in the image background on a pixel-by-pixel basis [47]. Using CCTV could be a good choice for outdoor parking; because few cameras can cover a whole parking lot [48].

2.3 Parking Reservations Systems (PRS)

Although PGI systems provide the drivers with information about the vacant parking spaces and may also give route guidance to them, this still does not solve the parking problems. This is due to the phenomenon of “multiple cars chasing the same spot” [12]. In fact this is the case in very dense traffic, and the consequences are not limited to an increase in traffic congestion, fuel waste, environmental damage, and driver frustration.

The development of Parking Reservation Systems (PRS) is a new concept in the area of ITS to provide the drivers with guaranteed reservations of parking spaces, such that there are no drivers’ arrival conflicts over parking spaces [8]. The merits of PRS are even beyond solving the traffic congestion problem, PRS systems can be optimised to maximise the parking resources utilisation and parking revenue, minimise the drivers cost function or both. A driver cost function sometimes consists of the actual parking price and the travel time or distance the driver has to spend to reach the parking space.

The basic components of PRS include a real time parking availability monitoring system, a parking reservation operations center (this is where the core reservation algorithms/model run), and a communication system between drivers and PRS [49].

2.3.1 Deterministic and Stochastic Parking Reservation System

This type of parking reservation systems basically assumes deterministic arrivals - the driver arrival time to the parking lot has to be known a priori - and there are sufficient parking resources to serve all the incoming vehicles arriving in one time interval [49]. The parking lot operation times are discretized into small time periods. When the time periods are smaller, the mathematical problem becomes more realistic as it becomes nearer to the actual pattern of drivers arrivals and departures. Drivers provide the system with their arrival times, their current geographical location and

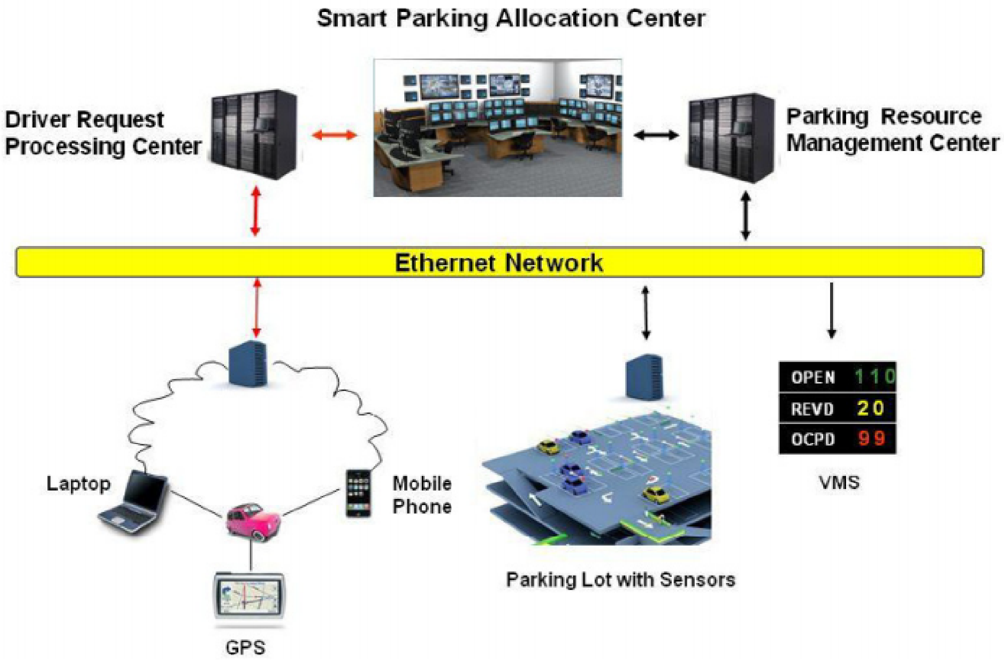


Figure 2.2: Dynamic resource allocation and parking reservation system architecture. [50]

their destination's geographical location. The system afterward either minimises the total effective cost for all drivers, maximises the parking utilisation/revenue or both. This forms a binary integer linear programming problem that can be solved with Linear Programming (LP). Moreover, by relaxing the exact arrival times to probability distributions, a stochastic formulation of the problem is produced.

Mouskos *et al.* [51] modelled this reservation process as a resource allocation problem. Their model is based on Mixed Integer Linear Programming (MILP) with the objective of minimising driver cost. The cost is a representation of the drivers' walking distance from the parking lot to destination and price of occupying the parking space. The arrival and departure times are deterministic and are specified by each driver. Small time periods are discretized from the total parking lot operation time. This produces a binary integer linear programming problem that is solved by a Linear Programming (LP) software. The problem formulation is described below.

First, key binary variables are defined:

$$x_{ijk} = \begin{cases} 1, & \text{if } i\text{th driver is parking at lot } j \text{ at time } k \\ 0, & \text{otherwise} \end{cases} \tag{2.1}$$

$$y_{ijk} = \begin{cases} 1, & \text{if } i\text{th driver parking at lot } j \text{ is departing at time } k \\ 0, & \text{otherwise} \end{cases} \tag{2.2}$$

Let Z_j be the capacity of parking lot j and c_{ijk} to be the cost of driver i to park in parking lot j at period k. Now the objective function that minimises the driver cost can be written as follows:

$$minimise \sum_{ijk} c_{ijk} \cdot x_{ijk} \tag{2.3}$$

Subject to:

(1) Each driver i is only allocated one parking lot resource.

$$\sum_{j} x_{ijk} = 1 \quad \forall i,k \tag{2.4}$$

(2) The number of drivers allocated to parking lot j at time k must be less than or equal the number of available parking spaces in lot j at k=1, where it is assumed that the parking lots are vacant at this time period.

$$\sum_{i} x_{ij1} \leq Z_j \tag{2.5}$$

(3) The number of drivers allocated to parking lot j at time k must be less than or equal the number of occupied spaces plus the vacant spaces due to drivers left at time k.

$$\sum_{i} x_{ijk} \leq z_j - \sum_{i} \sum_{k=1}^{k-1} x_{ijk} + \sum_{i} \sum_{k=1}^{k-1} y_{ijk} \tag{2.6}$$

(4) A driver *i* who occupy a parking lot *j* at time k is the same driver *i* that leaves parking lot *j* at time *l*.

$$x_{ijk} = y_{ijl} \quad \forall l = k \tag{2.7}$$

The work proposed by Mouskos *et al.* [51] is considered a universal parking reservation system [49]. Nevertheless, Geng *et al.* [12, 50] had extended their work by developing a dynamic resource allocation MILP model which allows the drivers to get re-allocated continuously a better parking resource until they are in the vicinity of their destination. In addition, several fairness constraints were included, such as adjusting the priority of allocating parking spaces to drivers in the basis of their proximity to their destinations. In [51], a driver has no control on expressing his/her interest in defining the cost. Whereas in [12], a driver sets a weight between 0 and 1 to express his/her interest in minimising either the walking distance or price. The model is then extensively simulated using a real world case study and it showed a vast improvement over the state of the art parking guidance systems. The general architecture of the systems proposed in [12] and [50] is shown in Fig. 2.2.

2.3.2 Pricing-based PRS Systems

The parking market can be steered using pricing policies. The utilisation of the limited parking capacity in high-demand areas can be improved by applying a more efficient management of the parking demand through the implementation of pricing policies [52]. Parking policies does not only affect the parking resource utilisation, it also directly affects the general traffic flow. For instance, under-priced parking leads to an increase in the traffic congestion, since it creates an economic incentive for drivers to cruise for the limited vacant parking resources [13]. A numerical analysis presented by Zhou [53], showed that increasing the on-street parking fees -

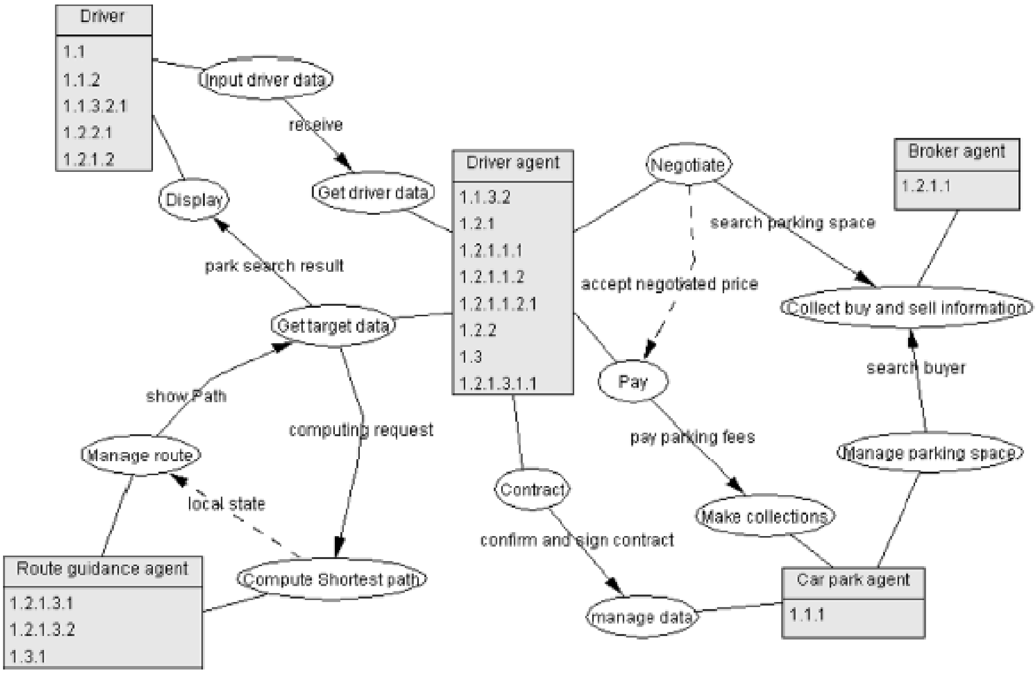


Figure 2.3: Intelligent agent parking system roles model [54]. In this figure, five roles are defined, indicated by the rectangles, including driver, driver agent, car park agent, route guidance agent and broker agent. The driver agent is the core role in a parking information system and all roles are associated with it. The broker agent registers and maintains abilities of the buyer and seller agents, and stores notices about goods sought and for sale. The ovals denote tasks that the role must execute in order to accomplish its goal.

which is under-priced - to an optimal level will reduce the number of searchers, and discourage individuals from parking their cars on the street.

Pricing-based PRS systems take into account different parking pricing policies, for example, in the form of negotiation [54–58], pricing differentiation [59] or dynamic pricing [60].

Pricing negotiation is usually carried out by utilising an intelligent agent system [61], as in Fig. 2.3, where agents are the representatives of the drivers and the car parks. With negotiation, the agents interact through a dialogue, exchange offers, evaluate other agents' offers and then modify their own proposals until all agents reach a satisfactory agreement [62]. Negotiation methodologies are usually based on game theory or influenced by natural human behaviours.

Chou *et al.* [54] proposed a PRS based on dynamic parking negotiation and guidance using agent-based method. In [54], the driver agent uses initiator negotiation algorithm with the car parks agents to bargain. The asking price of the driver agent is determined based on a boundary of minimum and maximum prices and the negotiation time. The asking price is continuously revised after the respondent's bid, until a negotiation result is decided. On the other side, the car park agent uses respondent negotiation algorithm to bargain, reject or accept proposals. When a car park agent receive a proposal from a driver agent, it will evaluate the parking availability and pricing from the resource database. Similar to the driver's agent bids, there is a boundary for a minimum and maximum bids a car park agent can respond within them and it is calculated based on the actual resource price, time of the day and the car park utilisation, to maintain a certain profit margin. The negotiation process is similar to the human negotiation process, such that, the buyer agent starts with the minimum bid, and the seller agent responds with the maximum bid, then both parties revise their bid to reach a satisfactory agreement. When the agents agree on a parking price, the driver is reserved this parking space and the system allow route guidance to the car park using a Geographic Information System (GIS) enabled device and Vehicle Information Communication System (VICS) in the driver's car.

longfei *et al.* [56] proposed a similar system [54], however they have grouped the car park agents of similar city district to a single parking information service center (PISC) that communicates with other PISCs and drivers' agents through a wireless network. This architecture reduces the average communication traffic and communicating times to a great extent. In addition, they have proposed different negotiation algorithms between the drivers' agents and car parks agents, such that agents propose their own price range based on the estimated value and the other party's initial price. The initial bids of both parties are estimated based on the parking demand.

Pricing negotiation can also be made using auctions to allocate drivers to parking resources. Hashimoto *et al.* [58] proposed a reservation system that is auction based, at which there is an interval for the reservation bidding process, drivers would need to register their bids before the deadline at which the system will allocate the spaces based on the highest bid. The interval for each reservation bidding process in decided by the parking manager for every parking time zone. For example, the parking manager decides the reservation bidding interval 9:30 to 10:00 for the 10:00 to 11:00 time zone. This system solely focus on increasing the revenue for parking managers.

Another approach to a pricing-based PRS system is pricing differentiation. Yan *et al.* [59] introduced a smart parking system which models the parking process as birth-death stochastic process. They have categorised a parking space either as economy class or business class. The economy class parking spaces are generally cheaper than business class ones, and they are the spaces with less quality than those of business class, e.g., far away from the gates.

Last, dynamic pricing can also be utilised in pricing-based PRS systems. Mackowski *et al.* [60] developed a dynamic pricing model for a smart parking reservation system which promises to reduce the drivers' cruising times and traffic congestion in busy urban centers and positively impact the local economy. The model utilises the real time information of parking demand and parking availability to update the pricing of parking spaces accordingly [60]. The objective of the model is to maintain an occupancy percentage for parking spaces of each block to 85%. This is achieved by varying the prices as follows: when the parking demand is increased, the prices are raised, and when the parking demand is decreased, the prices are lowered.

The concept of fixing the occupancy rate at 85% by dynamic pricing was first introduced by Shoup *et al.* [1], in order to reduce the cruising time for cheap on-street parking areas - as shown in Fig. 2.4. Later, this concept led to the development of San Francisco Park (SFPark) [63] in San Francisco. The aim is to overcome the traffic congestion by dynamically changing prices based on sensor historical data.

In SFPark, sensors are deployed on the asphalt to gather parking information that are stored in a database and processed weekly or monthly. According to historical data, the prices are increased and decreased proportional to the expected utilisation. Although dynamically changing parking prices shall balance the supply and demand for parking and increase overall utilisation, it is based on historical data and statistics which may not be accurate enough to have the proper effect. Thus, Mackowski *et al.* [60] proposed a new parking system to overcome this limitation by utilising real time parking data instead of historical data.

2.3.3 Mobile/Web Parking Information and Reservation System

The implementation of any PRS system requires a communication system between the drivers and the PRS operations center. The use of cell phones or web are hence a very popular and cheap way for exchanging and viewing information.

Trusiewicz *et al.* [64] used Unstructured Supplementary Service Data (USSD) as communication medium between divers and parking reservation system. Although it is not free to use USSD for most of network operators, it is still a cheap and reliable technology to adopt in parking reservations.

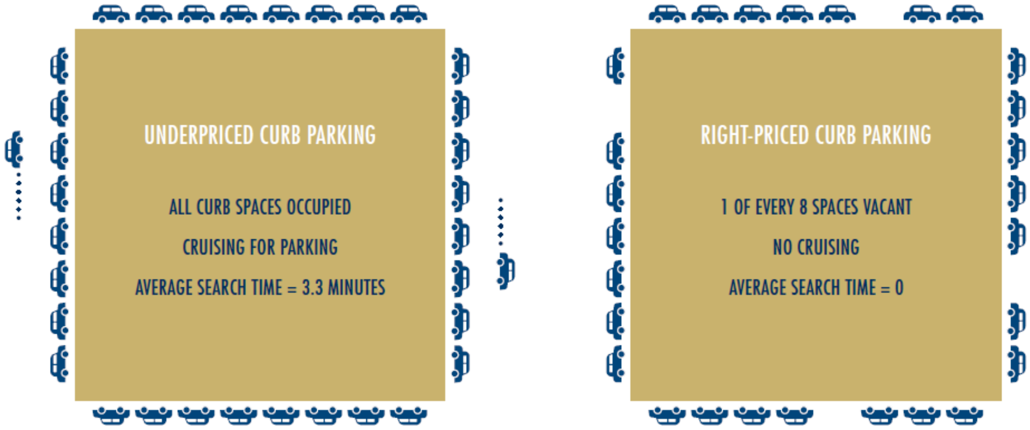


Figure 2.4: Curb parking prices and cruising. [1]

Inaba *et al.* [65] utilised RFID tags to store and update the reservations status and they discussed the difference between real-time and share-time reservations where the difference between them is that in share-time reservations, drivers must use the service in a known entry and exit time frame as they share the resource time. Whereas in real-time reservations, they are allowed to park for unlimited interval of time for being independent of other drivers. The drivers can reserve a parking space by a web site on Internet. The web site they developed provides real-time images of the parking spaces, so that the drivers can easily recognize the occupancy situation.

Wang *et al.* [66] introduced a prototype for a distributed system at which there is one central processor which gathers the reservation requests and redirects them to the relevant local processors. Their system utilises Blue-tooth and Wi-Fi to detect the occupancy states inside parking lots, and notify the drivers through a smart phone app with available spaces accordingly.

Short Message Services (SMS) reservations were presented in many research articles. For example, Hanif *et al.* [67] developed an embedded SMS reservation system using micro-controller, keypad, gate access control and a Remote Terminal Unit (RTU). Micro-RTU is a standalone terminal with a processor and a GSM module to receive SMS and trigger I/O pins. Reservation over the internet was demonstrated in [68] by using a sensor network of ZigBee and pressure sensors to detect the occupancy state of parking spots and the reservations were allowed using a website.

2.4 Transit-based Parking System

Park-and-Ride facilities refer to the parking lots with connections to public transport that allow commuters heading to city centres to park their vehicles and transfer to public transport for the rest of their journey. This saves the commuters the stress and frustration of driving along congested roads and finding scarce and expensive parking spaces. On the other side, this also may benefit the society and the environment by reducing the traffic congestion. Transit-based systems offer real time information on the availability of parking spaces in Park-and-Ride facilities as well as public transportation, e.g., bus and train schedules and traffic conditions.

San Francisco Bay Area Rapid Transit (BART) in California had implemented the first transit-based parking project in the United States. The assessment of traveler demand and behavioral effects shown that the average commuting time and the total vehicle miles of travel are reduced. It is also shown that nearly half of the commuters would not have used BART if smart parking were not available.

2.5 Automated Parking

In Automated Parking, driver drives up to a bay at the entrance of the parking lot, leaves the car and machines afterward move the vehicle automatically to its allocated spot. Automated parking is designed to provide more parking spaces for the same piece of land as compared to conventional multi-story car parking lots. This is achieved by providing parking on multiple levels stacked vertically. Since vehicles are transported by a mechanical system, the need for pedestrian walkways, drive lanes, ramps, stairways and elevators are eliminated, hence utilising the most of land use for storing cars only.

Additionally, Automated Parking offers several other advantages. For example, drivers need not to drive inside the parking lot cruising for a parking space, this effectively saves the drivers the time and effort and reduces the fuel emissions. Another advantage is the safety provided to vehicles and its contents.

2.6 Shortfalls of Current Smart Parking Systems

PGI and Transit-based Smart Parking systems both belong to guidance-based systems. In general, they are a vast improvement over unguided parking, however, they do not provide a complete solution. Guidance-based systems may increase the probability of finding free parking spaces, but in turn they change the driver's behaviour from searching to competing for parking. In addition, guidance-based systems are likely to be less viable in areas where: there is a high extent of drivers with local knowledge; numerous drivers have private car parking spaces; and there are noteworthy through traffic movements [69]. They may reduce travel time for drivers, however this reduction may be relatively small [70]. Furthermore, with guidance-based systems, even if drivers successfully found parking, they still may have missed parking at better parking spots. Another important fact is that guidance-based systems offer unfair balance of traffic, since parking spaces that are monitored will be utilised and traffic congestion will increase around, while unmonitored parking spaces will be left vacant [12].

In addition, each of the PGI sensors has its own drawbacks. For instance, the installation of sensors like pneumatic tubes, loop detectors, magnetic, acoustic and piezoelectric are complex and expensive for being intrusive [71]; they all require huge amount of asphalt digging which makes them expensive in terms of installation and maintenance. All of them are also sensitive to temperature and weather conditions [72]. Pneumatic tubes are especially sensitive to stress, acoustic sensors suffer from surrounding noise, ultrasonic and IR sensors are affected by temperature and air pressure. Active IR sensors suffer from degradation by obscurants in the atmosphere. These drawbacks lead to the fact that frequent maintenance is required for the systems utilising these sensors. Also, the common shortcoming is the need of power, either through cables or batteries.

PGI systems that depend on equipment placed inside the vehicles themselves, e.g., RFID, are very expensive to implement since it will be needed to install a RFID reader system for each parking space. In addition, this type of systems is user collaboration dependent, since all vehicles have to deploy a device, such as RFID tag, inside their vehicle [38].

CCTV also has its own drawback, for instance, it is sensitive to light intensity and weather conditions of outdoors, such that, shadows, vehicle projection, day-to-night transition, salt grim, icicles and cobwebs on camera lens can alter the detection accuracy [73]. On the other side, CCTV coverage for indoor parking is limited by the height from the ground to the ceiling which is typically less than 5 meters. This could make it an expensive approach for indoors, as the parking lot will need the mounting of numerous numbers of cameras.

PRS change the behaviour of drivers from driver side competition-based to system-based allocation and thus overcome many of the PGI limitations. However there still some significant shortcomings belonging to them. The main limitations of the deterministic PRS in [12] that is reviewed earlier are that reservations are only allowed for limited period of time (e.g., few minutes). Furthermore, fixed price was used and revenue was not taken into account and only a single choice of destination was considered. In fact, parking reservations in reality could be more appreciated if it is for the long-term (e.g., reservation for a week later to attend an event). In addition, city councils or private parking companies may not invest in such systems if their parking revenue is not improved.

Agent based PRS systems, e.g., [54–58], may need great improvements. For instance, car park and driver agents should utilise machine learning techniques to more flexibly adjust their bids. In addition, more reasoning capabilities to judge drivers' behaviour should be provided by driver agents. Thus, current agent based PRS systems are not mature enough to be implemented in real world applications.

Auction based reservation systems could lead to many fairness issues. For example, parking spaces will always be dominated by higher class people, or rich ones. Another problem may be the safety threat caused by bidding online through the mobile application while driving - as the bidding process may require driver's attention in order to win.

Mobile/Web Parking Information and Reservation Systems reviewed earlier indeed reduce the overall parking problems. However, they should not be utilised on their own. Instead, a smart parking reservation management model should be integrated to them, such that a general objective - e.g., maximise revenue or minimise cost - is achieved.

Automated parking systems automates the parking process inside an electro-mechanical parking lot once a vehicle arrives, but it is relatively expensive to deploy conveyor belts, rotatable lifts and shuttles to automatically move vehicle in a garage [12].

2.7 Summary

The searching for parking process is expensive and tiresome especially in major cities. From the driver's point of view, time, money and effort are wasted. From the Parking management point of view, parking resources are not well utilised and traffic is congested. From the environment perspective, carbon emissions are increased.

In order to solve these problems, ITS are developed. PGI systems utilise on-roadway or off-roadway sensors, controllers and transmitters to provide drivers with information about parking availability, in addition to pricing and navigation information in some cases. Transit-based parking systems is similar to PGI systems, however, they allow the commuters to smartly use the Park-and-Ride facilities to transfer from driving to public transport with the aid of parking and transportation information. Building on PGI systems, reservations are possible to guarantee parking spaces for drivers and avoid the competition on parking spaces. In addition, PRS systems may increase the parking resource utilisation and parking revenue and reduce traffic congestion. Automated parking automates the parking process using an electro-mechanical system that takes the vehicle from the driver at the park entrance and store it in its allocated space automatically.

Current smart parking systems have their own shortfalls such as: Guidance-based systems may increase the traffic congestion at monitored areas, multiple drivers may chase the same vacant spot and drivers may miss to park in better parking spaces. Also PGI sensors each has their own limitation, such as, complexity of installation, expensive maintenance, sensitivity to environmental changes and the need of power. Current PRS are not mature yet for use in practice because none of them offers in a single system all these together: flexible reservations options (near-future and far-future reservations), consideration of parking revenue as well as balancing the parking demand over the available parking supply. Finally, Automated Parking systems are relatively expensive to deploy. Hence, further improvements to the parking management and services are direly required.

Chapter 3

‘iParker’ – A Smart Car Parking System Based on Dynamic Resource Allocation and Pricing

3.1 Introduction

The work presented in this chapter combines parking reservation and pricing models to overcome the parking problems. In this chapter, we present a new smart car parking system, named iParker, with static resource scheduling, dynamic resource allocation and pricing models, to optimise the parking system for both parking managers and drivers. The merits of this work include: 1) increasing parking resource utilisation, 2) increasing parking revenue, 3) improving parking experience of drivers by lowering cost, parking spot searching and walking times. This system basically changes the conventional parking behaviour from driver-side parking searching and competition to system-side allocation. The majority of the parking issues in the present state-of-the-art guidance-based parking systems can be alleviated in our new system framework. iParker is designed to be implemented on a large scale, e.g., countrywide.

In this chapter we also propose a novel algorithm that is formulated as a Mixed Integer Linear Programming (MILP) problem to solve the parking resource allocation problem for iParker. Optimal allocation is obtained as a solution for each MILP based on current drivers and system state information and subject to random events, e.g., driver requests or parking sensors update. The model allows short-term dynamic reservations (few mins/hours ahead reservations, unbounded arrival-departure times and continuously allocating better parking resource until the driver reaches their destination) and long-term static reservations (many hours/days ahead reservations, bounded arrival-departure times, static reservations) with the objective of minimising the drivers' cost function and maximising the parking resource utilisation. The allocation ensures no reservation conflict, and that a set of fairness constraints are satisfied. Great improvements over unguided and guided-based systems are shown in the simulation results.

3.2 'iParker' System Overview

Our new concept is to combine real time reservations (RTR) with share time reservations (STR), thus a driver can reserve a spot while heading to it (*e.g.*, few minutes away) and also can reserve it at any time earlier (*e.g.*, many days away). RTR are achieved by performing dynamic resource allocation which is similar to skills based routing in call centers. In the case of RTR, drivers are constantly allocated the best parking spots available until they reach their destinations. Whereas STR are achieved by performing static resource allocation that is based on time scheduling where a driver can explicitly choose the preferred resource and the time frame at which it will be occupied at anytime in the future. Different pricing policies for both types of reservations that are fair for drivers and parking managers are proposed in this chapter. In addition, a dynamic pricing engine which periodically updates the parking prices based on real time resource utilisation by occupancy and reservations

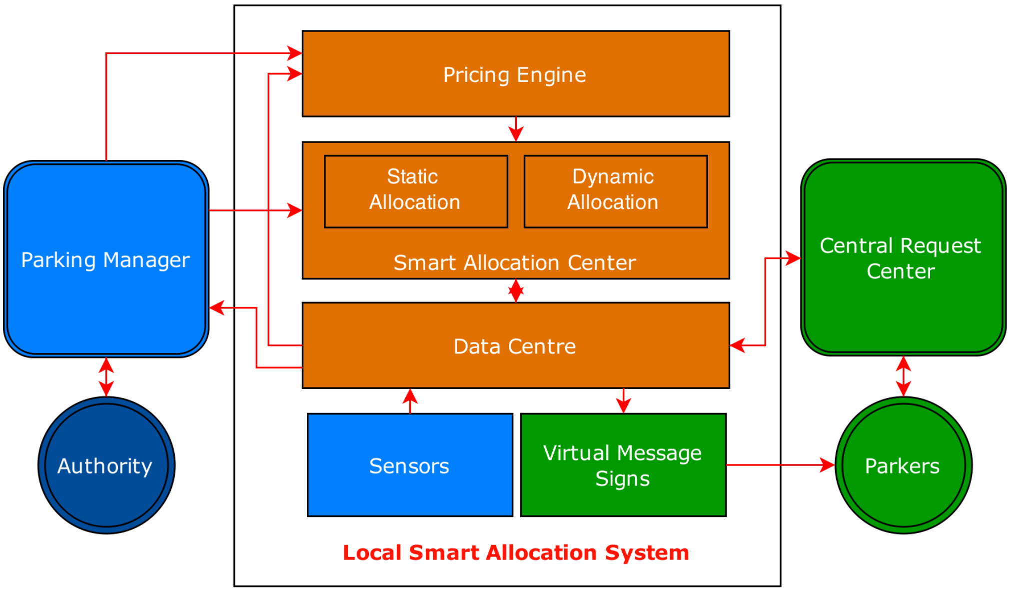


Figure 3.1: iParker framework.

and other events is introduced. iParker features the normal and disabled parking spots and drivers are given the freedom of choosing multiple destinations and the system will assign the optimal resources according to their chosen destinations and circumstances.

Throughout this chapter, we will employ the term ‘parker’ to refer to a driver or a car, ‘resource’ to refer to a group of parking spots, ‘D-Type’ to refer to a dynamic reservation, RTR or the type of a driver requesting a dynamic reservation and ‘S-Type’ to refer to a static reservation, STR or the type of a driver requesting a static reservation.

3.2.1 Architecture

iParker is a semi-distributed system as shown in Fig. 3.1: there are one Central Request Center (CRC), one Parking Manager (PM) and multiple local Smart Allocation Systems (SASs).

The CRC receives parkers’ requests, processes them and diverts them to the relevant local SAS. The request process is as following: parker chooses one to many destinations and if he/she is a S-type, preferred parking resource can be selected. Both types have to assign a weight parameter from 0-1 which reflects their desire between resource-destination proximity and resource price. Both types also set the maximum price and walking distance they can tolerate. For S-type, the spot occupancy interval has to be defined. For D-type, the GPS coordinates are measured and attached to the request. Finally the parker identifications (*i.e.*, driver and car license IDs) are accompanied with the request. CRC also responds back to all parkers with reservation offers and in the same fashion notifies the local SAS with parker's response.

The PM is a central parking manager who is an interface among parking authorities, parking resource managers, SASs and local pricing engines. Parking authorities can use the PM to manually update the relevant pricing engine or data centre. For instance, to fix pricing values for certain parking resource or update the data centre with upcoming events near a relevant resource.

Below we describe the main components of a local smart allocation system:

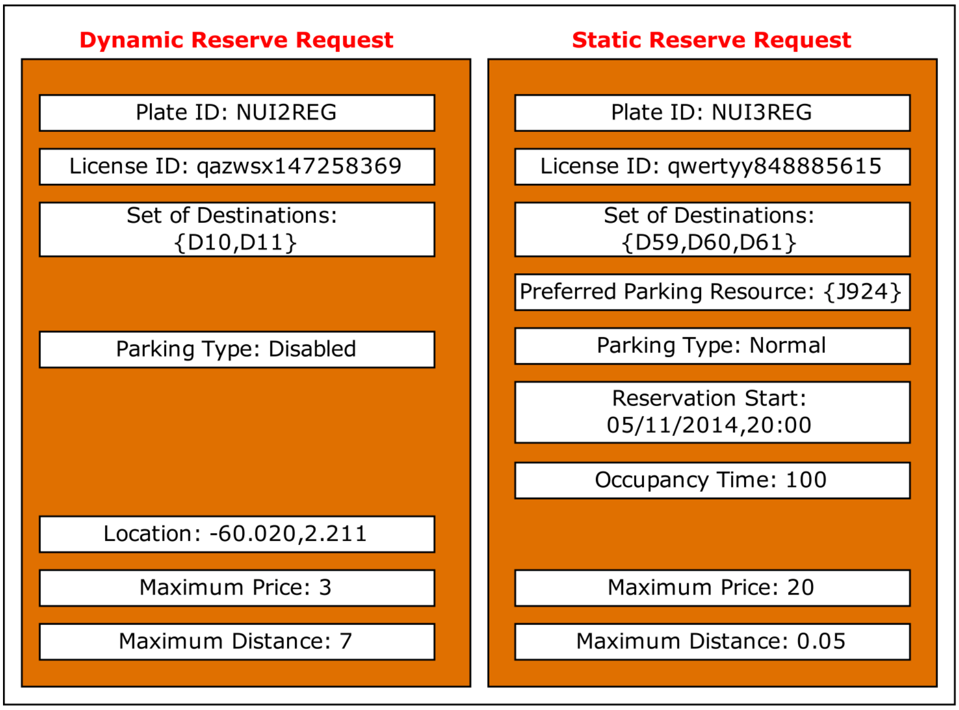
- **Pricing Engine -** Pricing engines are small applications that run a pricing model on web-servers. The duties of a pricing engine are to fetch parking utilisation data and updates from parking authorities every predefined time interval and to set the new parking prices accordingly. The engine runs independent of the SAS, calculates the new prices and updates the data centre.

- **Sensors -** Every resource is occupied with a spot occupancy detection system. Ideally this system must provide accurate data on the utilisation of the parking resource, either deployed indoors or outdoors. The detection system is normally composed of a wireless/wired sensor network that can provide occupation state of every parking spot, or alternatively composed of counter sensors at the entrance and exit of parking lots that is only capable of providing total utilisation value. The later method can only work in controlled environments, therefore we prefer to use sensor networks and a central processor that updates the data centre with the utilisation values.

- **Data Centre -** Holds all the information from all iParker components and store them in a structured data container. It’s consisted of a pricing table which contains the up to date information on pricing per resource per minute, utilisation table which holds the utilisation data, and finally authority table which stores other parameters that is set by parking authorities (*e.g.*, events related). A Data Centre is also responsible for updating multiple types of virtual message signs and public devices of up to date pricing information and parking availability.

- **Smart Allocation Centre -** A web service that runs a sophisticated MILP model that optimally and fairly assigns/reserves parking resources to the parkers. The assignment is based on key variables that are not limited to driver constraints, current resource utilisation, up to date pricing information and events occurrences. The centre provides non stop parking reservation service to the parkers and is described in details in the next section.

- **Virtual Message Sign (VMS) -** Updates parkers/public with up to date pricing and parking availability information. This is achieved by deploying numerous numbers of VMS panels across cities especially around on-street parking areas. For off-street parking lots, one VMS panel at the entrance is sufficient to inform arrivals of updated information. It is important to mention that a parker will only pay according to the price rate fixed in the reservation offer. If the parker is not using the service, he/she will pay according to the price rate displayed at the time of his/her parking. VMS is specially and critically important for non smart-phone.



Dynamic Reserve Request

Plate ID: NUI2REG
License ID: qazwsx147258369
Set of Destinations: {D10,D11}
Parking Type: Disabled
Location: -60.020,2.211
Maximum Price: 3
Maximum Distance: 7

Static Reserve Request

Plate ID: NUI3REG
License ID: qwertyy848885615
Set of Destinations: {D59,D60,D61}
Preferred Parking Resource: {J924}
Parking Type: Normal
Reservation Start: 05/11/2014,20:00
Occupancy Time: 100
Maximum Price: 20
Maximum Distance: 0.05

Figure 3.2: Parking request samples.

3.2.2 Reaction Scheme

Below we describe the reaction scheme between parkers, parking managers and iParker.

- **Parking Request -** As shown in Fig. 3.2, every parking request is accompanied with a pre-registered Parker Identification (PID) code which maps in the CRC to the basic identity of the parker which includes: Driver License Identification (DLID), Plate License Identification (PLID), and parker type (normal/disabled). In addition, parking requests contain the information about the reservation types (D-type/S-type), parkers’ locations and parkers’ constraints on walking distance and price. The request is then transmitted in the format of Extensible Markup Language (XML) to the CRC which then diverts the request to the relevant local SAS whose responsible of the requested destinations.

- **Resource Allocation -** The Smart Allocation Centre (SAC) fetches all the requests in the queue every predefined interval and then solves the MILP problem - that we will formulate in the next section. The SAC optimally allocates the resources for all parkers according to their individual circumstances. For D-type parkers, the cheapest resources and/or the nearest-to-destinations resources would be allocated to the parkers. For S-type parkers, the SAC will try to allocate the preferred resources to the parkers, and will treat them as D-type parkers if it failed. Following allocation, the SAC responds to all parkers with reservation offers. The resource allocation algorithm will be discussed in details in the next section.
- **Parking Response -** If a parker accepts a reservation offer, the system guarantees that the allocated parking resource is available on parker’s arrival. If the parker is of D-type, the SAC will keep assigning a better resource if found available until the parker reaches the destination. If the parker is of S-type, the SAC will allocate a parking resource only once. If a parker rejects the reservation offer, the SAC may assign different parking resource, but the parker will take the risk of getting a worse parking resource or no assignment.
- **Pricing and Payment -** The pricing for a D-type parker is calculated based on a pricing engine factor (real-time parking resource utilisation dependent), parker’s reservation time and the cost of the physical parking resource occupancy. Whereas the pricing for a S-type parker is calculated based on a flat reservation fee and the cost of the physical parking resource occupancy. Parkers register their debit/credit cards in their iParker accounts and the payments are taken automatically. Parking and reservations fees are flexibly managed by the parking managers through the PM WEB interface.
- **Reservation Guarantee and Enforcements -** Enforcements are smartly achieved by processing data fetched from parking detection sensor nodes and by co-

operating with parking enforcements officers through their Personal Digital Assistants (PDAs). Once a parking resource is occupied, the system immediately starts a verification process of legal parking by performing the following tasks: Learn about the reservation status of the parking resource. 1) If the resource is reserved, a parking confirmation request is sent to the parker reserving that resource asking the parker to verify if he/she had occupied that parking resource. 2) If the parker responded positively, the tasks break and the system register the parking event as a legal parking. 3) If however the parker responded negatively, a note with the parking resource identification is sent to the relevant parking enforcement officer to process a fine for the illegal parker. 4) If the resource is not reserved, task (3) is performed.

In the case of illegal parking, a portion of the fine given to the illegal parker goes to the driver who legally reserved that spot if he/she exists that fully compensate for his/her loss. In order to prevent illegal parking to happen in the first place, a simple lighting scheme can be integrated in the car park to display to the drivers the status of the parking spaces using colors. The red color can indicate a reserved space, the orange can indicate an occupied space and green represents a vacant space.

3.3 Smart Resource Allocation

The problem addressed in this study combines the real time and share time reservation systems. Real time reservations are typically independent of the amount a parker will consume in a parking space, *i.e.*, a parker can spend as much time as he/she needs without affecting the rest of the parkers. On the other hand, share time reservations are dependent of the exact spot occupancy and spot leave times. Share time reservations are generally modeled as birth-death stochastic processes. In our model, dynamic reservations are real time and static reservations are share time.

Table 3.1: Summary of notations

Notation	**Definition**
K	Decision point in time.
$DW(K)$	Set of parkers in DWAIT queue.
$SW(K)$	Set of parkers in SWAIT queue.
$DR(K)$	Set of parkers in DRESERVE queue.
$SR(K)$	Set of parkers in SRESERVE queue.
$Z(K)$	Set describing the # of vacant spots in all resources.
$\mathbb{P}1$	# of normal parking spots for dynamic reservations.
$\mathbb{P}2$	# of normal parking spots for static reservations.
$\mathbb{P}3$	# of disabled parking spots for dynamic reservations.
$\mathbb{P}4$	# of disabled parking spots for static reservations.
$g_i(K)$	Set of resources that contains at least 1 free parking spot.
$\sigma(K)$	Set of free normal parking resources.
$\bar{\sigma}(K)$	Set of free disabled parking resources.
$\mathbb{L}_j$	Location of resource j.
$C_j(K)$	Price per hour for occupying resource j.
$x_{ij}(K)$	Binary variable describes if parker i is allocated resource j.
$l_i(K)$	Location of parker i.
$V_i(K)$	Driving speed of parker i.
M_i	Maximum total price that parker i can afford to pay.
D_i	Maximum total walking distance that parker i can tolerate.
$M_{ij}(K)$	Actual price parker i should pay if allocated resource j.
$D_{ij}(K)$	Actual walking distance parker i if allocated resource j.
$J_{ij}(K)$	Total cost function of parker i if allocated resource j.
φ_i	Type of parking spot that parker i needs.
β_i	Type of reservation that parker i requests.
sw_i	Parker's weight between price and proximity.
$\psi_i(K)$	Time spent in DRESERVE queue.
$\omega_i(K)$	Wandering time of parker i.
T_i	Total occupancy time of parker i.
$\tau_{ij}(K)$	Remaining driving time between parker i and resource j.
$\upsilon_i(K)$	Reserved resource j by parker i.
$P_{ij}(K)$	# of dynamic spots in resource j that are feasible for parker i.
$\bar{P}_{ij}(K)$	# of static spots in resource j that are feasible for parker i.
θ	Occupancy interval starting time.
ϑ	Occupancy interval ending time.
$\Theta_{ivj}(K)$	Binary variable describes the state of conflict between static parkers.
$E(K)$	Matrix of conflict of interest between static parkers.
$t_0(K)$	Maximum allowed time of dynamic reservations.
$\Pi_i(K)$	Set of feasible resources for dynamic parkers.
$\Phi_i(K)$	Set of feasible resources for static parkers.
$\mathbb{F}_i(K)$	Set of feasible resources for any parker i of any type.

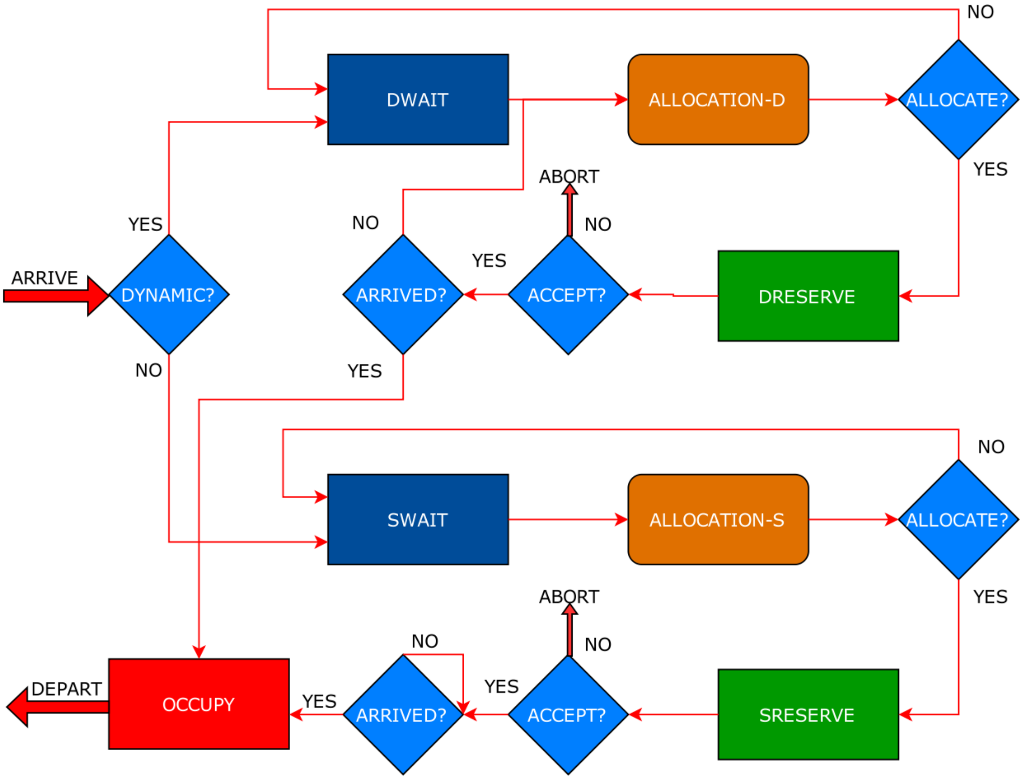


Figure 3.3: Queuing model flow.

The objective of our MILP model is to minimise the total monetary cost for parkers and ultimately maximise the total resource utilisation to obtain the maximum revenue for parking managers. We will formulate our model based on the queuing model in Fig. 3.3. There are N resources in which every resource j is split into $\mathbb{P}1$ spots (number of normal parking spots for dynamic reservations), $\mathbb{P}2$ spots (number of normal parking spots for static reservations) $\mathbb{P}3$ and $\mathbb{P}4$ (similar to $\mathbb{P}1$ and $\mathbb{P}2$ but for disabled people). The running time of the smart allocation centre is discretized into small time periods. We will denote each time period as a decision point K. All parkers arrive to the allocation center randomly and independently joins the relevant WAIT queue. At each decision point, the allocation centre will allocate resources to dynamic and static parkers and move them to the relevant RESERVE queue. Parkers in the dynamic reserve queue (DRESERVE) will get re-allocated a better parking spot (if available) after each decision point until they reach a defined

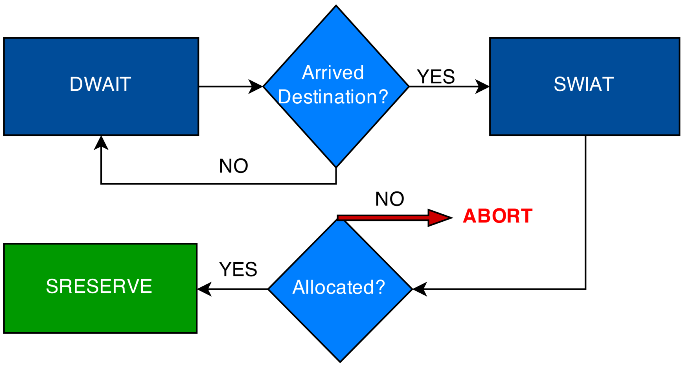


Figure 3.4: Static-dynamic reservations interface.

zone defined as their first destination. Parkers in the static wait queue (SWAIT) will only get allocated once and then move to the static reserve queue (SRESERVE). When parkers arrive to their resources, they will be moved to the occupy queue and then $\mathbb{P}1$, $\mathbb{P}2$, $\mathbb{P}3$ or $\mathbb{P}4$ will be decremented by the number of parkers. When parkers leave the parking spaces, they will be completely removed from the system and again the count of spaces would be incremented. To fully maximise the utilisation of resources, we will initialize the system by making 50% of the resources to be 'dynamic' and 50% to be 'static'. Then we will follow the strategy in Fig. 3.4: when parkers in DWAIT queue reach their destination and fail to get allocated for the reason that $\mathbb{P}1$ or $\mathbb{P}3$ became zero (*i.e.*, no free parking spaces for dynamic reservers), the system automatically diverts them to SWAIT queue, such that they get a chance for allocation for the 'static' resources.

3.3.1 Problem Formulation

At each decision point K, we will define the state of the smart allocation system $A(K)$ and the state of parkers $X_i(K)$ as follows (see Table. 3.1 for the list of definitions):

$$A(K) = \{DW(K), SW(K), DR(K), SR(K), Z(K)\} \tag{3.1}$$

$$X_i(K) = \{l_i(K), \psi_i(K), \upsilon_i(K), \omega_i(K), \mathbb{F}_i(K)\} \tag{3.2}$$

The key input of the allocation system is the feasible resources $\mathbb{F}_i(K)$ that each parker is eligible for. To formulate this, we define some major attributes for parkers. 1) M_i is the maximum total price that parker i can afford to pay. 2) D_i is the maximum total walking distance that parker i can tolerate. 3) φ_i is the type of parking spot that parker i needs. 4) β_i is the type of reservation. 5) $P_{ij}(K)$, $\bar{P}_{ij}$ and $g_i(K)$ are parameters that describe the state of parking resources and are explained later.

Below we define some key binary variables:

$$\varphi_i = \begin{cases} 1, & \text{if } i \text{ is requesting a normal resource} \\ 0, & \text{if } i \text{ is requesting a disabled resource} \end{cases} \tag{3.3}$$

$$\beta_i = \begin{cases} 1, & \text{if } i \text{ is requesting a dynamic reservation} \\ 0, & \text{if } i \text{ is requesting a static reservation} \end{cases} \tag{3.4}$$

$$\upsilon_i(K) = \begin{cases} j, & \text{if } i \text{ is reserved the resource j} \\ 0, & \text{otherwise} \end{cases} \tag{3.5}$$

By defining $\mathbb{L}_j$ as the location of the resource j, the remaining distance $d_{ij}(K)$ and driving time $\tau_{ij}(K)$ at time K between parker i and resource j can be estimated as follows:

$$d_{ij}(K) = ||l_i(K) - \mathbb{L}_j||$$

$$\tau_{ij}(K) = \frac{d_{ij}(K)}{V_i(K)} \tag{3.6}$$

Now it is possible to set a pricing scheme for parker i's first attribute $M_{ij}(K)$ as a function of $\tau_{ij}(K)$, $\psi_i(K)$, T_i (the total occupancy time) and $C_j(K)$ (the current price per hour for occupying resource j). As shown in (3.7), we charge the dynamic parker a reservation fee that is equivalent to his/her total reservation time. On the other hand, we charge the static parker a flat reservation fee equivalent to the price of an occupancy hour.

$$M_{ij}(K) = \begin{cases} (\frac{C_j(K)}{60})(\psi_i(K) + T_i + \tau_{ij}(K)), & \text{if } \beta_i\text{=1} \\ (\frac{C_j(K)T_i}{60}) + C_j(K), & \text{if } \beta_i\text{=0} \end{cases} \tag{3.7}$$

For both static and dynamic parkers, we allow them to choose multiple destinations. $\mathbb{DL}_i = \{\eth 1_i, \eth 2_i, ..., \eth nd_i\}$ is the set of locations of the destinations $\mathbb{D}_i = \{1, 2, ..., nd\}$ chosen by parker i with $\eth 1_i$ being the first destination. A parker can choose up to nd destination. Parker i's second attribute $D_{ij}(K)$ can now be formulated to express the total traveling time on foot. Equation 3.8 allows the allocation system to identify the nearest resource j to parker i according to his/her chosen destinations $\mathbb{D}_i$.

$$D_{ij}(K) = \sum_{n \in \mathbb{D}_i} ||\eth n_i - \mathbb{L}_j|| \tag{3.8}$$

Now we can calculate the total cost function $J_{ij}(K)$ that we will minimise for parker i according to the weight $sw_i = [0-1]$. For instance, if parker i wants the cheapest resource, then $sw_i = 1$ is the choice. If parker i is only interested in the best spot in terms of walking distance, then $sw_i = 0$ is the choice.

$$J_{ij}(K) = sw_i \frac{M_{ij}(K)}{M_i} + (1 - sw_i) \frac{D_{ij}(K)}{D_i} \tag{3.9}$$

Remark: We have employed the grouping spot technique in this model to save computational power, such that a resource j may have N number of spots. For example, $\mathbb{P}1_j = 1$, $\mathbb{P}2_j = 2$, $\mathbb{P}3_j = 3$ and $\mathbb{P}1_j = 4$ means that in resource j, there are 1 normal-dynamic, 2 normal-static, 3 disabled-dynamic and 4 disabled-static free spots.

For dynamic parkers, the allocation system must be fed with data from parking sensors in real-time. Therefore we define $P_{ij}(K)$ as the number of free dynamic spots in resource j that is compatible for parker i’s parking type. We also define $g_i(K)$ as the set of resources that contains at least 1 free parking spot. $g_i(K)$ will be equal to either the set of free normal parking resources denoted as $\sigma(K)$ or the set of free disabled parking resources denoted as $\bar{\sigma}(K)$.

$$P_{ij}(K) = \varphi_i \mathbb{P}1_j(K) + (1-\varphi_i)\mathbb{P}3_j(K) \tag{3.10}$$

$$\sigma(K) = \{j : j \in Resources, \mathbb{P}1_j(K) > 0\}$$

$$\bar{\sigma}(K) = \{j : j \in Resources, \mathbb{P}3_j(K) > 0\}$$

$$g_i(K) = \begin{cases} \sigma(K), & \text{if } \varphi_i = 1 \\ \bar{\sigma}(K), & \text{if } \varphi_i = 0 \end{cases} \tag{3.11}$$

$\Pi_i(K)$ can now be defined as the set of feasible resources that can be allocated to dynamic parkers. $\Pi_i(K)$ is determined by filtering all the resources to match with parker i’s highest boundaries on price and proximity (M_i and D_i). If resource j is from the same type (normal/disabled) that parker i demands, there are free parking spots of that kind and boundary requirements are met, j will be added to Π_i at decision time K.

$$\begin{aligned} \Pi_i(K) = \{j : M_{ij}(K) \le M_i, D_{ij}(K) \le D_i, \\ P_{ij}(K) > 0, j \in g_i(K)\} \end{aligned} \tag{3.12}$$

We will employ different approach to define the feasible resources for static parkers. As we mentioned earlier that static reservations are share-time reservation system. Thus the allocation system will allocate resources to static parkers according to the availability of free parking spots at the occupancy starting time for parker i and of course according to parker's requirements.

We define $\bar{P}_{ij}$ as the total number of static spots in resource j that is compatible for parker i's parking type, *i.e.*,

$$\bar{P}_{ij} = \varphi_i \mathbb{P}2_j + (1 - \varphi_i)\mathbb{P}4_j \tag{3.13}$$

$\Theta_{ivj}(K)$ is then computed which is a binary variable equal to 1 if there is a conflict in occupancy intervals of parker i in $SW(K)$ and parker v in SW(K), $SR(K)$ and static occupy queues, on a resource j of the same kind. Occupancy interval starts at θ and ends at ϑ, *i.e.*,

$$\Theta_{ivj}(K) = \begin{cases} & if((\theta_{vj} \geq \theta_{ij}) \wedge (\theta_{vj} \leq \vartheta_{ij}))| \\ 1, & ((\theta_{ij} \geq \theta_{vj}) \wedge (\theta_{ij} \leq \vartheta_{vj}))\wedge \\ & (\varphi_i = \varphi_v) \wedge (\beta_i = \beta_v) \wedge (i \neq v) \\ 0, & \text{otherwise} \end{cases}$$

Then we define matrix $E(K) = [\Theta_{ivj}(K)]$ and introduce the key array $conflict_{ij}(K)$ which allows the resource allocation for static parkers such that

$$conflict_{ij}(K) = \sum_{i \in SW(K), j \in Resources} E(K) \tag{3.14}$$

Based on $conflict_{ij}(K)$ and parker requirements, it is possible to compute the feasible resources for static parkers $\Phi_i(K)$ as follows:

$$\begin{aligned} \Phi_i(K) = \{ j : M_{ij}(K) \leq M_i, D_{ij}(K) \leq D_i, \\ conflict_{ij}(K) < \bar{P}_{ij}(K), j \in Resources \} \end{aligned} \tag{3.15}$$

We will combine all parkers together (dynamic and static) in one objective function. This can be achieved by introducing $\mathbb{F}_i(K)$ as the set of feasible resources for each parker i of any type.

$$\mathbb{F}_i(K) = \begin{cases} \Pi_i(K), & \text{if } \beta_i = 1 \\ \Phi_i(K), & \text{if } \beta_i = 0 \end{cases} \tag{3.16}$$

3.3.2 Objective Function

From the parker's point of view, iParker minimises the overall parker cost in terms of price and proximity. From the parking managers' point of view, iParker maximises the resource utilisation and generates revenue. We introduce the binary decision variable $x_{ij}(K)$ such that

$$x_{ij}(K) = \begin{cases} 1, & \text{if parker } i \text{ is assigned resource } j \\ 0, & \text{otherwise} \end{cases} \tag{3.17}$$

and define matrix $X(K) = [x_{ij}(K)]$. Now we can formulate the objective function and constraints for our problem that is solved at each decision point K:

$$\begin{aligned} \mathit{minimise} \sum_{i \in DW(K) \cup DR(K)} \sum_{j \in \mathbb{F}_i(K)} x_{ij}(K) \cdot J_{ij}(K) \\ + \sum_{i \in DW(K) \cup SW(K)} (1 - \sum_{j \in \mathbb{F}_i(K)} x_{ij}(K)) \end{aligned} \tag{3.18}$$

s.t.:

$$\sum_{j \in \mathbb{F}_i(K)} x_{ij}(K) \leq 1 \quad \forall i \in DW(K) \cup SW(K) \tag{3.19}$$

$$\sum_{i \in DW(K) \cup DR(K) : \varphi_i = 1} x_{ij}(K) \leq \mathbb{P}1(K) \quad \forall j \in \sigma(K) \tag{3.20}$$

$$\sum_{i \in DW(K) \cup DR(K) : \varphi_i = 0} x_{ij}(K) \leq \mathbb{P}3(K) \quad \forall j \in \bar{\sigma}(K) \tag{3.21}$$

$$\sum_{j \in \mathbb{F}_i(K)} x_{ij}(K) = 1 \quad \forall i \in DR(K) \tag{3.22}$$

$$\begin{aligned} &(\sum_{n \in \mathbb{F}_i(K)} x_{in}(K)) - x_{mj}(K) \geq 0 \\ &\qquad \forall i, m \in DW(K), j \in \mathbb{F}_i(K) \\ &\quad s.t. \;\; \tau_{mj}(K) > \tau_{ij}(K), \varphi_i = \varphi_m \end{aligned} \tag{3.23}$$

$$\sum_{j \in \mathbb{F}_i(K)} x_{ij}(K) \cdot J_{ij}(K) \leq J_{ij}(K-1) \quad \forall i \in DR(K) \tag{3.24}$$

$$x_{ij}(K) \cdot t1_{ij}(K) \leq t_0(K) \quad \forall i \in DW(K), j \in \mathbb{F}_i(K) \tag{3.25}$$

The objective function in (3.18) can be split into 2 parts, $\sum_{i \in DW(K) \cup DR(K)} \sum_{j \in \mathbb{F}_i(K)} x_{ij}(K) \cdot J_{ij}(K)$ and $\sum_{i \in DW(K) \cup SW(K)} (1 - \sum_{j \in \mathbb{F}_i(K)} x_{ij}(K))$. In this problem we minimise the objective function and this will have two effects according to the mentioned parts. The first part aims to minimise the total monetary cost in (3.9) for all parkers in $DW(K)$ and $DR(K)$, such that parker i will be assigned the resource j in his/her feasible resources $\mathbb{F}_i$ with the least J_{ij}. Note that we did not include the parkers from $SW(K)$ nor $SR(K)$; because static parkers do get allocated only once and for the j of their choice. If we did not add the second part to the equation, the system will not allocate any parkers by setting all $x_{ij}(K)$ to zero. Therefore we introduce the second part to allocate as much parkers as possible in the $DW(K)$ and $SW(K)$. Resource allocation will be maximised because J_{ij} by its definition is less than 1, thus adding a cost of 1 to the objective function is satisfactory enough to guarantee maximum resource allocation.

The constraints in this problem can be described as follows:

- **Capacity -** 1) constraint (3.19) ensures that all parkers in $DW(K)$ and $SW(K)$ cannot be assigned more than one resource. Also it indicates that those parkers might not get allocated, *i.e.*, $x_{ij}(K) = 0$. 2) constraints (3.20) and (3.21) indicate that the sum of numbers of dynamic parkers who are going to get reservations (parkers in $DW(K)$) and parkers who already got reservations earlier (parkers in $DR(K)$) must be less than the total unoccupied spots at time K.

- **Reservation guarantee -** Constraint (3.22) guarantees that every parker i in $DR(K)$ must retain their allocation. Note here that parkers in $SR(K)$ are not mentioned. This is because static parkers (by the definition of the objective function) get allocated once and they do not enter the allocation system again once allocated and therefore their reservation guarantee is also true.

- **Cost guarantee -** All kinds of reservation systems must commit to the offer or quotation they supply to the customer, and this is what constraint (3.24) will achieve. The system will record all the parkers' cost J at every decision time K and it will ensure that it does not reallocate any parker to a resource j with cost higher than $J(K-1)$. Also note that $SR(K)$ is not mentioned in the constraint; because a static parker will choose the preferred resource j that he/she wants to occupy. Thus the value of J of that parker will never change.

- **Fairness -** Constraint (3.23) indicates that if parker i is located nearer to his/her feasible resources $\mathbb{F}_i(K)$ as compared to parker m such that $\tau_{mj}(K) > \tau_{ij}(K)$ and parkers i and m are requesting the same parking type, then a priority of allocation would be given to parker i such that $x_{mj}(K)$ must be set to 0 if $x_{ij}(K)$=0.

To further maximise the resource utilisation by 'dynamic' parkers, constraint (3.25) is introduced where we define $t_0(K)$ to be the threshold at which a parker must be $t_0(K)$ further away from destination in order to be eligible for dynamic allocation.

$t_0(K)$ is set dynamically according to the real-time resource utilisation following the rules in Table 3.2.

Table 3.2: Utilisation vs. t_0 vs. price factor

Utilisation (%)	**0**	**10**	**20**	**40**	**60**	**80**	**100**
t_0 (min)	120	50	30	20	10	2	0
Price Factor (%)	25	30	50	70	100	135	200

Utilisation: percentage of occupied spots in a parking resource. t_0: maximum allowed time of dynamic reservations. Price Factor: a percentage to be multiplied by the original total parking price to yield the parking price in dynamic pricing mode.

3.3.3 Dynamic Pricing Engine

We also examine the effect of dynamically changing the prices of occupying spots in real time fashion based on real-time utilisation data of each resource j rather than changing them every couple of days or months based on historical data. The dynamic pricing engine will operate every predefined minutes to update prices according to the rules in Table 3.2.

Table 3.2 will be utilised as following: if a resource j=1 at a given time K=1 with all parking spots free and an original price $C0_1$, the spot price at this time would be set to $C_1(K)$= $0.25 * C0_1$ because utilisation is found to be 0%. Now if utilisation increased to 60%, the engine will increase the price to the full original price $C0_1$. Similarly when the utilisation further increases, the price increases till its maximum (200% of the original price) and when the utilisation falls, the price will drop to its minimum (25% of the original price).

The motivation behind dynamic pricing is to introduce a fair balance of utilisation and revenue across all parking resources which in turn will assist in reducing overall traffic congestion. It is important to note that pricing change would only take effect on parkers in WAIT queue. Which means that a parker who already got a reservation or occupied a spot will be paying at the same rate that was fixed for him/her at the time of reservation/occupation.

In order to realize this in practice and for drivers who will not use iParker, VMSs should be deployed nearby the parking resources to show the latest pricing information and the time at which the next pricing update would be made.

3.3.4 Algorithm and Implementation

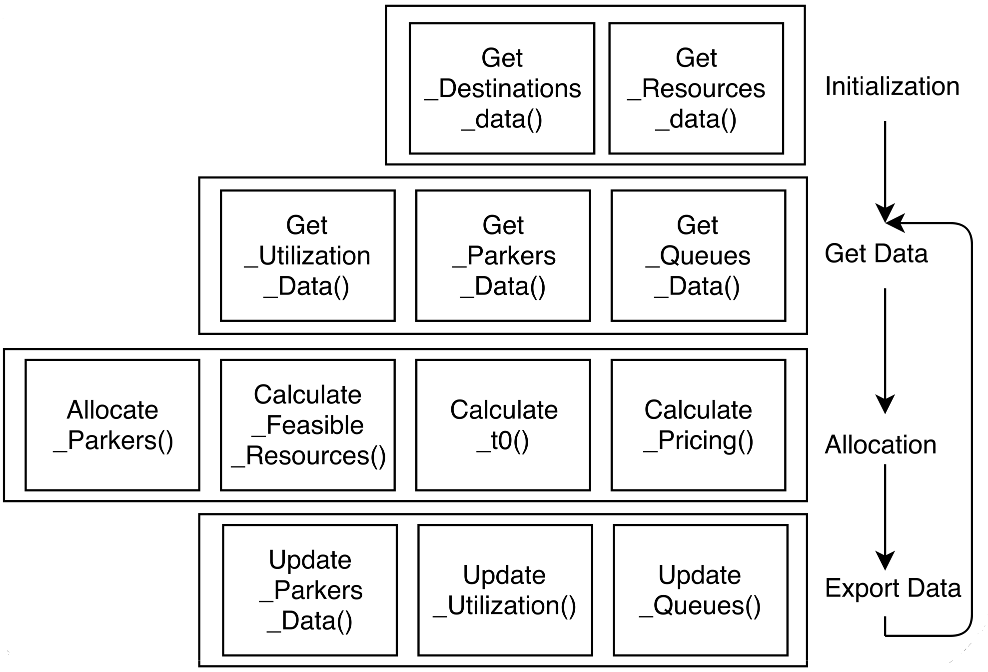


Figure 3.5: Program algorithm overview

The software used to solve the MILP problem is IBM ILOG CPLEX (CPLEX). In order to evaluate the system effectiveness, sets of data are first randomized to represent the data of parkers, resources, destinations and pricing. Using Microsoft Excel, the parkers arrivals are generated following Poisson distribution and the rest of parameters are generated following exponential distribution. A database is then created to store the random data and act as the storage node for the CPLEX program. The CPLEX program that is discussed in Fig. 3.5 inputs the random data generated earlier and updates the database after the parkers’ allocation.

3.4 Results and Discussions

3.4.1 Performance Metrics

From the point of parker's view, smart parking should cost less (either in terms of money or walking distance or searching time or all). On the other hand, from the point of parking managers' view, smart parking should provide the highest resource utilisation and generate the highest revenue. Thus we define the following main performance metrics:

- Total Utilisation - is the total average resource utilisation and we denote it as U_avg. We also break it down in the simulation results to parking (UP), reservation (UR), normal-parker (U_Normal_avg) and disabled-parker ($U\_Disabled\_avg$) utilisation.

- Revenue - is the revenue generated and we break it to on-street and off-street revenues in the simulations.

- Searching Time - is the average time spent by a parker from the time of reaching their destination to the time of physically occupying it.

- Total Cost - is the average total cost incurred to a parker who ultimately had occupied a parking resource and can be formulated as

  $TotalCost = \frac{1}{3}(2(sw_i\frac{M_{ij}(K)}{M_i} + (1-sw_i)\frac{D_{ij}(K)}{D_i}) + \frac{SearchingTime_i(K)}{SearchingTime_{max}})$

- Wandering - is the ratio of parkers who arrived to their destination, however they could not find or get allocated an available parking resource.

By adding "$-on$" or "$-off$" to any of the metrics, we denote to on-street and off-street respectively. Also note that "D" refers to "Dynamic" and "S" refers to "Static".

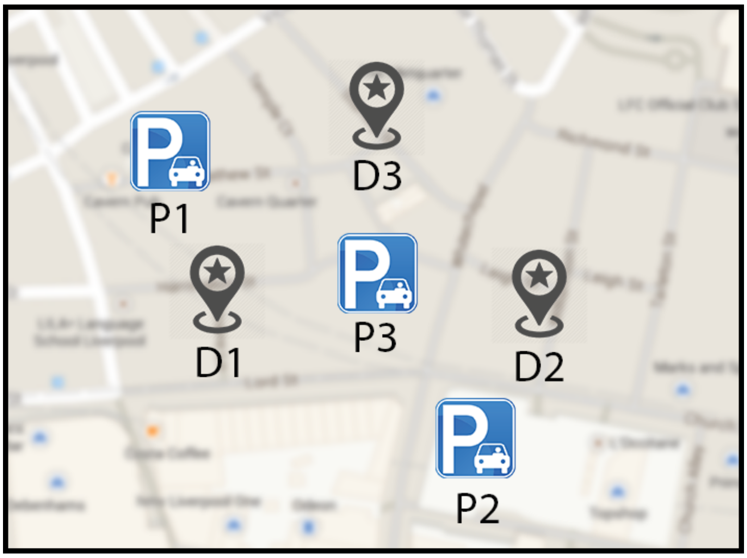


Figure 3.6: Simulation case study environment.

Table 3.3: Simulations setup parameters

R	M_i	D_i	$t1_i$	T_i	**A.R.**	$v2$	**D.A.**	**S.A.**
ℙ1:70 ℙ2:30 ℙ3:8 ℙ4:4	0-8 GBP	0-1 KM	30 min	60 min	N: 1 D: 2+	5 KM/h	70 %	30 %

R: Resources. A.R.: Arrival Rate (N: Normal and D: Dense). D.A.: Dynamic Arrivals. S.A.: Static Arrivals. GBP: Great Britain Pound. KM/h: kilometer per hour.

3.4.2 Simulations Setup

In this section iParker system is denoted as Smart-Parking (SP), guided system as (G) and non guided as (NG). G is modeled to be a smart parking system but without reservations and it is described as following: parkers know about the real-time availability of parking resources, their pricing and their proximity to their targeted destinations. Parkers in G will minimise their cost exactly as in SP. As for NG, parkers do not have any information about parking resources availability nor price information. In NG system, parkers will search for a free tolerated parking resource in an increasing radius method till they occupy it (See Appendix C for more information about G and NG parking methodology). The values in Table 3.3 will be used in all simulations.

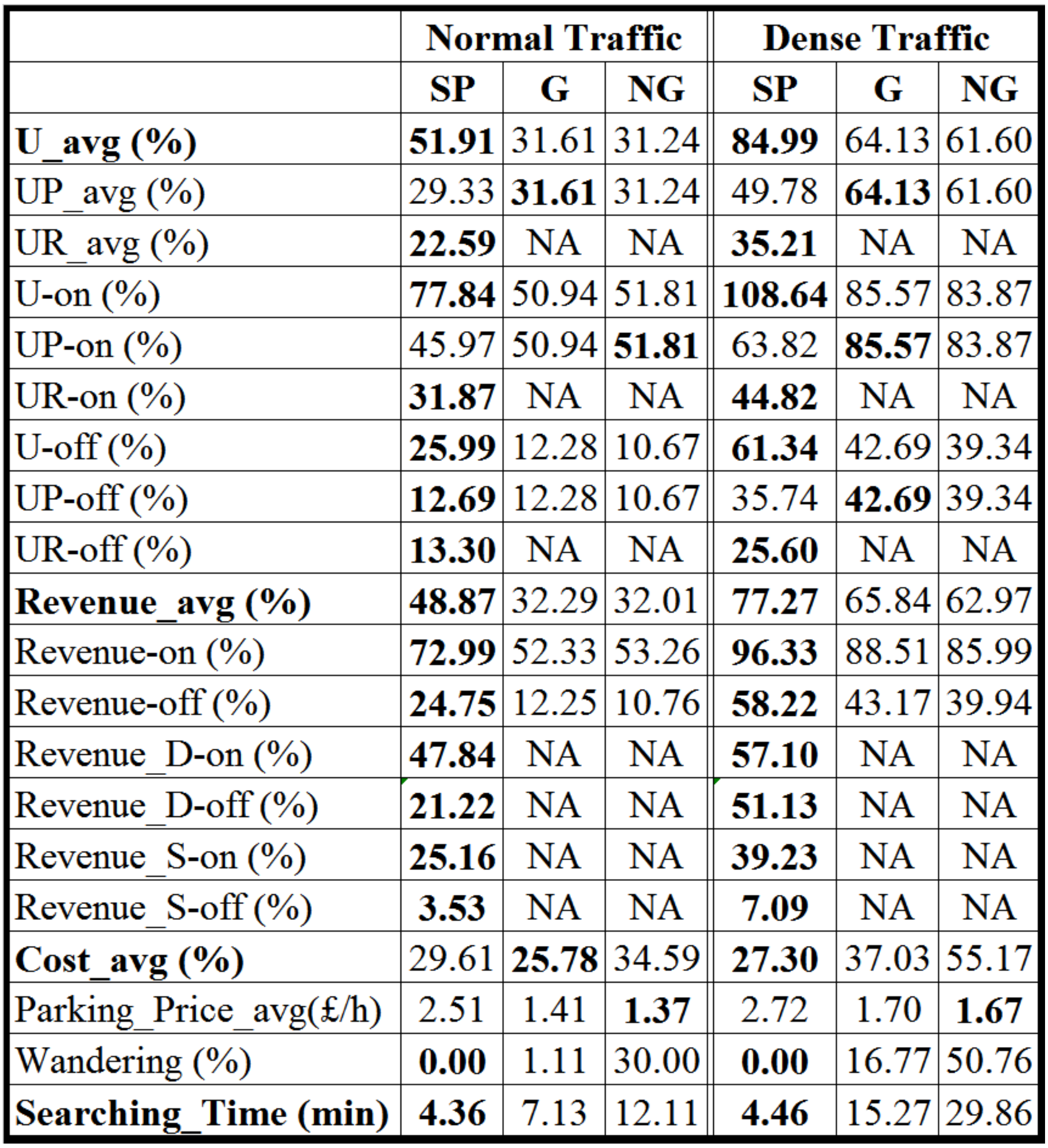
In Fig. 3.6, we show the parking environment that we have used in the simulations. There are 56 On-street parking spots split into two parking resources and 56 off-street parking spots in one parking resource. There are also 3 destinations that parkers are going to choose to arrive to. We set the initial resources variables as following: $\mathbb{P}1$=70, $\mathbb{P}2$=30, $\mathbb{P}3$=8 and $\mathbb{P}4$=4. M_i and D_i are uniformly distributed from [0-8] GBP and [0-1] KM respectively. Travel times $t1_i$ and resource occupancy times T_i are exponentially distributed with the rate of 30 minutes and 60 minutes respectively. Arrival rates are following Poisson distributions with rate 1.0 representing normal traffic and rate greater than 2.0 representing heavy traffic. In all simulations we set the percentage of dynamic arrivals to 70% and static arrivals to 30%, also we assume that 10% of all arrivals are disabled. The conversion from distances to time is based on the assumption that drivers drive on an average speed of $v2 = 5$ KM/h in the destination and parking regions, talking into account the effect of traffic and number of stops.

Finally in simulations III we performed them using variant arrival rate similar to simulations II. However, because we specifically wanted to evaluate the effect of using real-time dynamic pricing on the overall system, we have fixed D_i to a large value close to infinity and fixed sw_i to 1 such that parkers are only interested to minimise their parking price cost. We also modified the case study in Fig. 3.6 such that all the parking lots are on the same price (2 GBP) and the same proximity to destinations.

3.4.3 Scalability

MILP problems are NP-Hard and the time consumption of problem solving is highly proportional to the problem complexity. In addition, the static allocation part of our problem gets more time consuming as the parkers reserve resources in the late future. In our problem, it is critical to obtain a solution at each decision point in a

Table 3.4: System performance using uniform arrival rates



	Normal Traffic			**Dense Traffic**		
	SP	**G**	**NG**	**SP**	**G**	**NG**
U_avg (%)	**51.91**	31.61	31.24	**84.99**	64.13	61.60
UP_avg (%)	29.33	**31.61**	31.24	49.78	**64.13**	61.60
UR_avg (%)	**22.59**	NA	NA	**35.21**	NA	NA
U-on (%)	**77.84**	50.94	51.81	**108.64**	85.57	83.87
UP-on (%)	45.97	50.94	**51.81**	63.82	**85.57**	83.87
UR-on (%)	**31.87**	NA	NA	**44.82**	NA	NA
U-off (%)	**25.99**	12.28	10.67	**61.34**	42.69	39.34
UP-off (%)	**12.69**	12.28	10.67	35.74	**42.69**	39.34
UR-off (%)	**13.30**	NA	NA	**25.60**	NA	NA
Revenue_avg (%)	**48.87**	32.29	32.01	**77.27**	65.84	62.97
Revenue-on (%)	**72.99**	52.33	53.26	**96.33**	88.51	85.99
Revenue-off (%)	**24.75**	12.25	10.76	**58.22**	43.17	39.94
Revenue_D-on (%)	**47.84**	NA	NA	**57.10**	NA	NA
Revenue_D-off (%)	**21.22**	NA	NA	**51.13**	NA	NA
Revenue_S-on (%)	**25.16**	NA	NA	**39.23**	NA	NA
Revenue_S-off (%)	**3.53**	NA	NA	**7.09**	NA	NA
Cost_avg (%)	29.61	**25.78**	34.59	**27.30**	37.03	55.17
Parking_Price_avg(£/h)	2.51	1.41	**1.37**	2.72	1.70	**1.67**
Wandering (%)	**0.00**	1.11	30.00	**0.00**	16.77	50.76
Searching_Time (min)	**4.36**	7.13	12.11	**4.46**	15.27	29.86

reasonable time interval. Therefore, the following strategies are considered to reduce the size of the problem and are adopted in the next simulations: 1) Grouping: The number of resources can be very much reduced by grouping resources together. Such that, a resource will contain several parking spaces (*e.g.*, a parking lot or a street). Similarly, destinations that are close can be grouped. 2) Area splitting: If the number of resources and destinations are still very large, the area can be split to a number of sub-areas where a problem will be solved for each. 3) Reservations control: The dynamic reservations can be limited by discriminating users who are very far away from their destinations. Whereas the static reservations can be limited by reducing the time frame at which a parker can reserve a spot (*e.g.*, 1 week).

3.4.4 Uniform Arrival Rate

The results in Table 3.4 prove the concepts behind our system. From the parking managers' point of view, the total average utilisation increases by 21% which represents 16% and 14% increase in revenue as compared with non-guided and guided systems, respectively. Although the utilisation by parking (denoted by UP) is higher in other systems compared to SP, the total utilisation by SP is the highest due to the introduction of dynamic and static reservations. The effect of dynamically varying $t_0(K)$ can be seen in the results as the U-on of SP in dense traffic is lower than that of G and NG. We expected this to occur as by definition of (3.25). When the parking spaces are close to being saturated, $t_0(K)$ approaches zero. This happens more quickly for on-street parking in dense traffic because they are much cheaper than off-street parking, therefore the SP system allocates the incoming arrivals to off-street parking till the on-street utilisation decreases. This however can be considered as an advantage because it has introduced a good balance of utilisation between different parking resources which in turn balances the general traffic flow.

On the other hand, from the parkers’ point of view, SP proven to offer parkers the lowest combined cost as compared to G and NG. For instance, in dense traffic, the total cost is reduced by 28% and 10% as compared to NG and G respectively. Although the cost in terms of money in SP due to reservations is higher than other systems, the overall parker satisfaction is higher when using SP. This is clearly shown in the results for dense traffic where the searching time is decreased in SP by about 25 minutes as compared to NG and 11 minutes as compared to G. The increase in searching time in G in dense traffic is mainly due to the phenomenon of ’multiple cars chasing the same spot’. The dramatic increase of searching time in NG is due to the fact that they search for available spaces blindly. Also SP has the lowest cost because of the zero wandering time (the time spent when a parker arrives destination and finds no available parking space). The wandering ratio for parkers in NG increases by about 20% in dense traffic as compared to normal traffic and by about 16% in G.

3.4.5 Variant Arrival Rate

The merits of iParker are more visualized in Fig. 3.7 and Fig. 3.8, where we have performed another simulations with variant arrival rates from high rate in the morning and in the evening and low rate in the afternoon. The second simulation results agree with the first simulation results in terms of maximising the utilisation parking resources, increasing revenue and minimising parkers’ cost.

However there are a few things to note here: 1) the revenue at 7 PM for SP is greater than 1. This could normally happen when the parking resource is near to be fully occupied and taking into account that the fees for reservation is added on top. 2) the total cost of parkers is not reduced in SP as compared to G in the times with low arrival rate. This is because in G, the cost is minimised exactly like in SP and when the arrival rate is low, the probability of wandering in G is close to zero and therefore the searching time is minimal. This however can be solved by reducing the reservation fees at the times of low arrival rate. 3) the searching time in SP is about constant throughout the day, which confirms that our model does not allow wandering for users and thus decreases the overall traffic congestion.

We compared our system with that of [12] and it is shown in Fig. 3.8 that our model yields on average about 5% more utilisation, 40% less searching time and 18% more revenue. The increase in utilisation and revenue is clearly because our model allows static reservations and also the reservation time threshold for dynamic reservations is not fixed as in [12]. Finally an increase of 4% in the total parker cost is seen and this is because in [12], they do not charge fees for reservations. These conclude that our model does outperform the one in [12].

Table 3.5: Performance metrics with different dynamic-static resource ratios

DR:SR	**10:90**	**30:70**	**50:50**	**70:30**	**90:10**
Cost	0.34	0.34	0.34	0.33	0.33
Revenue	0.50	0.53	0.55	0.56	0.54
Utilisation	0.45	0.47	0.48	0.49	0.48

Most of the parameters used in the simulations are set to be dynamic and are not fixed except for the parameter that sets the ratio between the resources that are configured for dynamic reservations to the static ones (DR:SR). Table 3.5 shows the main performance metrics with different DR:SR under variant arrival rate. The table shows DR:SR=70:30 having the best results. The reason is that the arrival rate is set to 70:30 for parkers as shown in Table 3.3. However the changes observed are negligible. This proves the good efficiency of the dynamic-static interface discussed earlier. Therefore the DR:SR=50:50 will be reasonable to be the default setting as the parkers' choices between dynamic and static reservations in real world will not be constant.

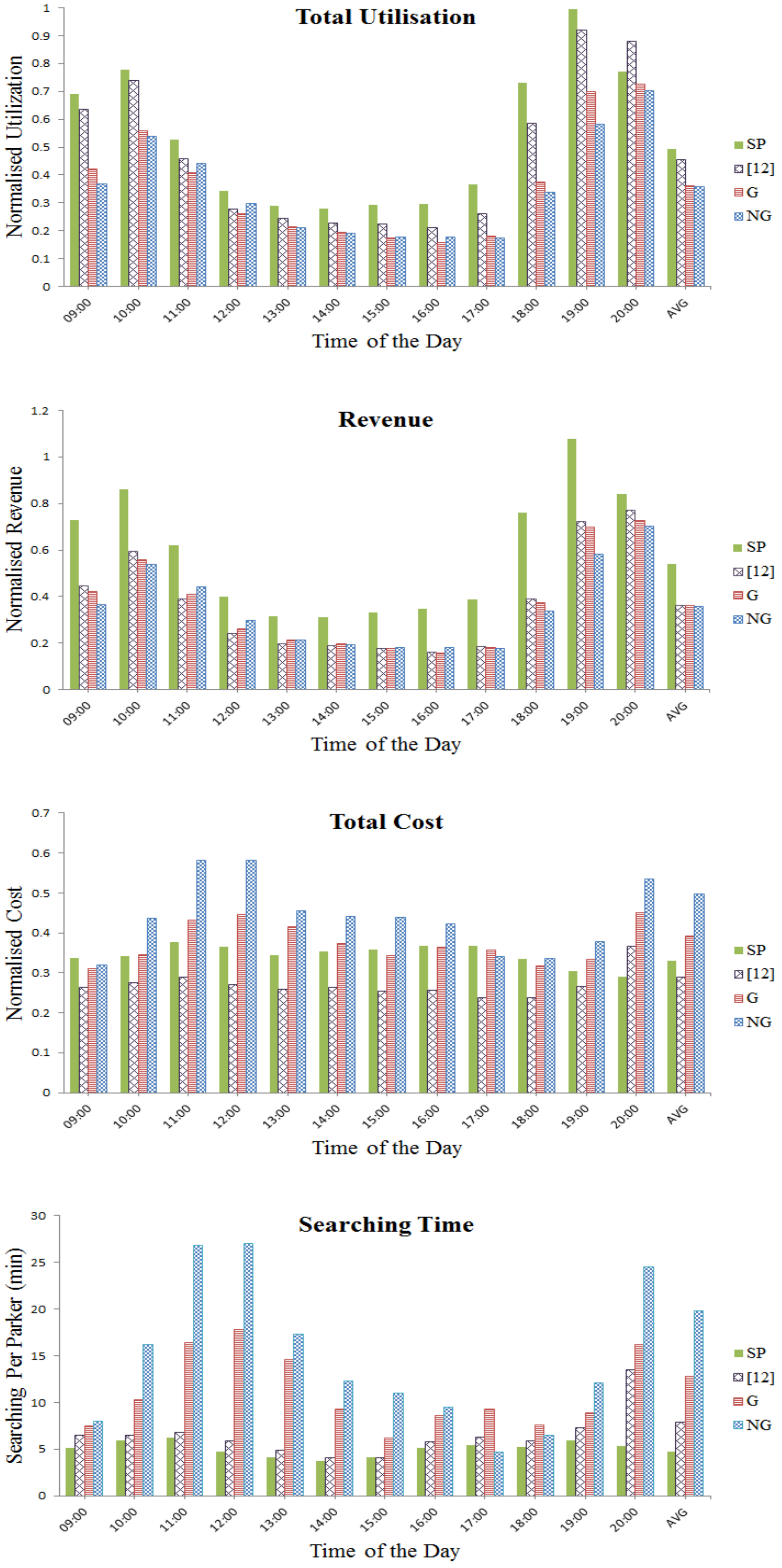


Figure 3.7: Performance metrics using variant arrival rate.

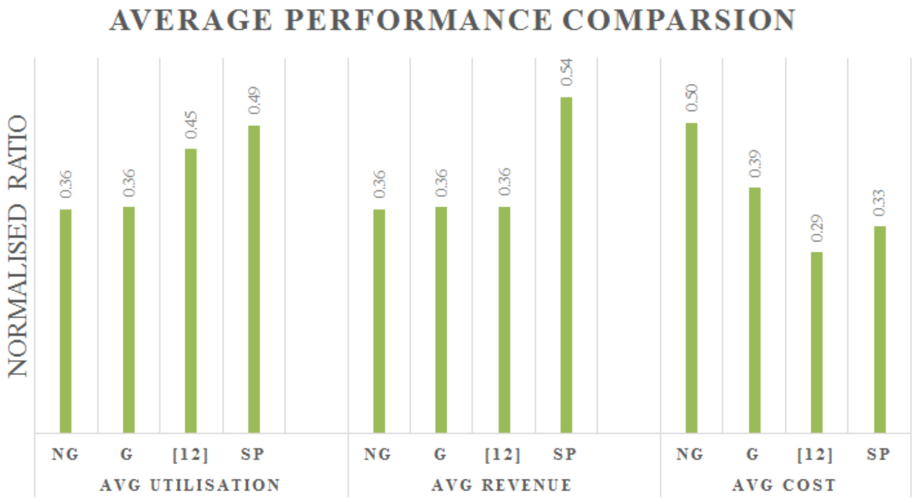


Figure 3.8: Average system performance comparison using variant arrival rate.

3.4.6 Dynamic Pricing

In this section, we explore the effect of dynamically varying the resource pricing according to real time utilisation measure using the scheme in Table 3.2 and we present the results in Fig. 3.9. It is observed as expected that by continuously changing the prices of resources, we can control and limit the utilisation of those resources. Furthermore, these changes results in a fair balance of utilisation between parking resources which in turn assist in reducing the overall traffic congestion caused by parking. The average utilisation of the parking resource 1 is higher than that of other resources when using fixed pricing. On the other hand, a significant change occurs when using dynamic pricing, such that the average utilisation of the 3 parking resources are close to identical. In Fig. 3.10, we show the average results obtained during dynamic and fixed pricing to further analyse the pricing engine. It is shown that dynamic pricing doesn't change the percentage of the total utilisation of parking resources, either by parking or revenue. However, a negligible change in revenue and cost is observed, which can be tweaked by changing the parameters in Table 3.2.

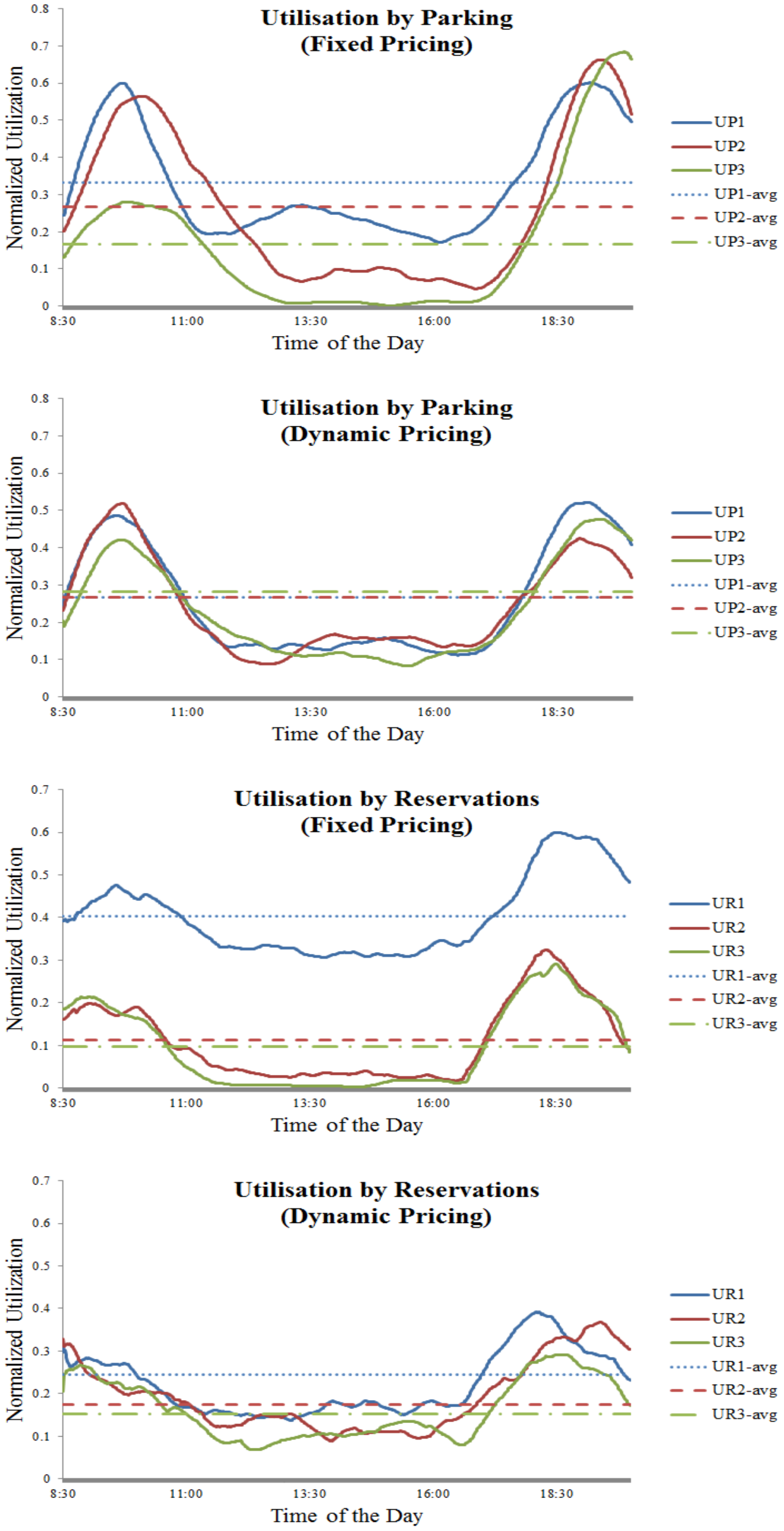


Figure 3.9: Utilisation comparison under fixed and dynamic pricing. The comparison is between parking resources 1, 2 and 3.

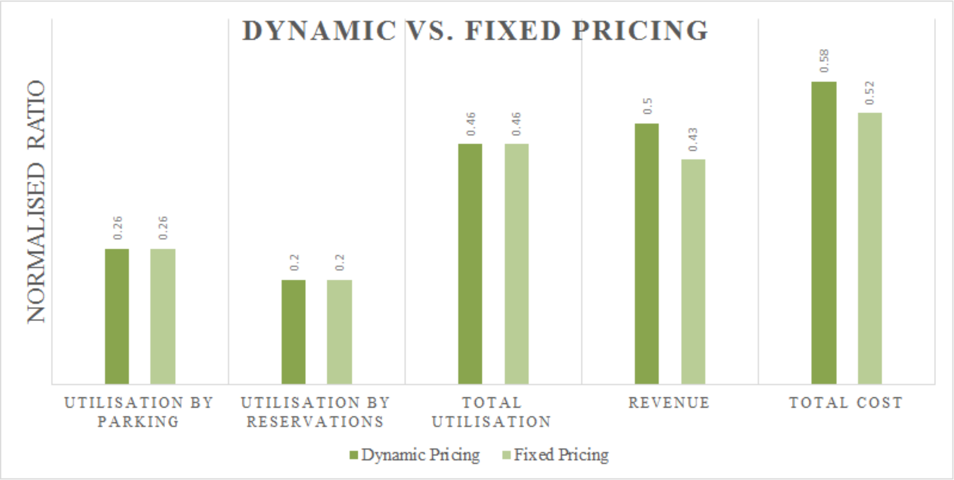


Figure 3.10: System performance comparison under dynamic and fixed pricing.

3.5 Conclusions

In this chapter we have proposed iParker, a new smart parking system which is based on MILP model that yields optimal solution for dynamically and statically allocating parking resources to parkers - providing flexible reservation options. The new concepts introduced in this chapter are the combination of real-time reservations with share-time reservations, dynamically performing system decisions (reservation time constraints and pricing) according to real-time utilisation information, and offering the drivers the choice of choosing multiple destinations and reservation type. We also have proposed pricing policies for both static and dynamic reservations that maximises the profit from parking. Extensive simulation results indicate that the proposed system significantly cuts the total effective cost for all parkers by as much as 28%, maximises the total utilisation by up to 21% and increases the total revenue for parking management up to 16% as compared to the non-guided parking system. Finally, we proposed a dynamic pricing scheme and by integrating it to iParker's model, we found by simulations that it balances the utilisation across all the parking resources and thus assist in eliminating the overall traffic congestion caused by parking.

Chapter 4

‘INDO’ – A Smart Indoor Commuting and Car Parking System Based on RFID/NFC, Resource Allocation and Navigation

4.1 Introduction

Indoor navigation is becoming an important and attractive research field, especially since the introduction of smart phones [74]. The motivation behind it is to reduce the searching time either for locating a place, a person or an object, and to provide a better experience. Nowadays, most of the large buildings (e.g., shopping malls, museums, schools, etc..) contain a parking lot with hundreds or even thousands of parking spaces. The commuting time of a visitor typically consists of the following stages: 1) driving from the park entrance to a vacant parking space. 2) walking from the parking space to the building entrance. 3) walking from the building entrance to the points of interest. 4) walking all the way back to the parking space and driving out of the park.

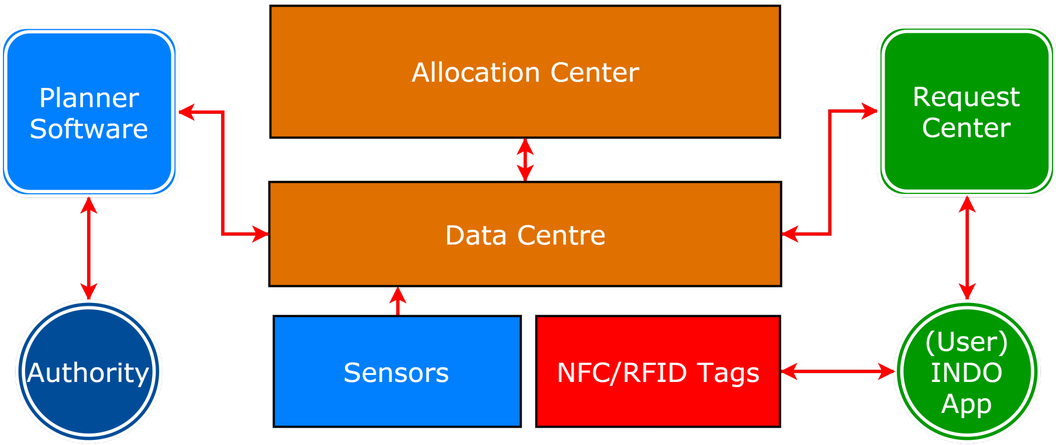


Figure 4.1: INDO framework.

In order to reduce the total commuting time, indoor navigation systems can be utilised for guiding the visitors indoors to find any points of interest quickly [75]. On the other hand, smart parking systems are able to increase the speed of finding a vacant parking space and reducing the time of wandering around [76].

Current indoor navigation and guidance systems inside buildings and smart parking systems are independent and unconnected which bring the motivation behind our work. In this chapter, we have combined the merits of indoor navigation systems and the merits of parking reservation systems under one platform. The main contributions of our work include: 1) Modeling and simulating the users’ commuting process indoors under both, unguided and guided situations. 2) Formulating and simulating a new Mixed Integer Linear Programming (MILP) model that allocates the optimal parking resources, the entrance and the exit gates of the car park, and the building. The model significantly reduces the total commuting time for all users. 3) Designing and developing an indoor navigation solution based on the Cell of Origin (COO) localisation principle that requires minimal hardware and computing resources.

4.2 ’INDO’ System Overview

The concept of this system is to minimise the total commuting time of users seeking to park and visit known destinations inside an indoor building. This is achieved by allocating the optimal parking space for the users and providing them with an indoor navigation solution that allows them to navigate indoors and to return to their car. Therefore INDO’s main system responsibilities are the parking resource allocation and the indoor navigation for users.

For the former, the system needs to have the information about the car park and indoor building layouts and points of interests (POIs). In the meantime, we will refer to those information as digital maps. POIs could be a parking space in the car park or a place inside the indoor building. The resource allocation, as discussed in details later in this chapter, is performed based on the parking availability, digital maps and the users’ information - such as users’ chosen places inside the building. The objective of the resource allocation is to allocate parking spots to users that results in the minimisation of their total commuting time. To achieve this, the following shortest routes have to be computed: 1) From the main entrance/exits to the parking spots. 1) From the parking spots to the building entrances/exits. 2) From the building entrances/exits to the indoor POIs. Following that, the walking/driving distances are calculated for those routes and are stored in the system database. Now whenever a user request to visit a POI inside the building, the system solves the MILP problem - that is described and formulated later in the chapter - to identify the parking spot which yields the minimum total walking/driving distances, based on the information previously stored in the database and the user’s chosen location.

Now that the users are allocated the optimal parking spaces, they are still at the risk of wasting their time in wandering around indoors to reach their destinations. In addition, users may forget the locations where they have parked their cars. The second responsibility of INDO is guiding the users indoors to reach their destinations via the shortest possible routes and also guiding them returning back to their cars. This is achieved by utilising the information stored in the database that are discussed previously. A smart phone application is developed to utilise those information and hardware, e.g., RFID or NFC, for the indoor navigation process. The indoor navigation component of this system is described in details later in Section 4.3.

INDO is a standalone system that will be implemented separately for any building, e.g., shopping mall, museum, etc.. Its main components as depicted in Fig.4.1 are described below:

- **Request Center -** It is a server application that makes the interface between the users and the Data Centre. The Request Center receives parking requests from the users, which are made of the unique users IDs, users location, chosen destinations and the type of the parking parking space - normal or disabled. Following that, the Request Center records those requests as a database entries in the Data Centre. When the Allocation Centre allocates parking resources to the users, the Request Center informs the users through their smart phone application with their allocation results. The Request Center is also responsible of notifying the system with the acceptance or decline of the allocation offers given to the users.

- **Planner Software -** It is a Windows based software that converts floor plans into digital maps. Each map carries the information about the routes between what is called ”nodes' and ”points of interest' (POIs). For parking areas, a POI is inserted for each parking space. Following that, the administrator inserts nodes at the areas where possible user turns could occur. Every node could be linked to other nodes forming a route and could be linked to POIs. In contrast, the planning is similar for the indoor building, however, the POIs are inserted for places of interest, e.g., a shop or a toilet.

The software also automatically links a unique electronic product code (EPC) for every node or POI, such that it can be programmed into RFID/NFC tags to be used in indoor navigation. In addition, the digital map also contains a cost report that carries the information about the distances between all the POIs and the building gates/entrances/exits, which will be used by the allocation system for calculating shortest path routes and effectively allocating parking spaces. Last, the digital maps are exported to the Data Centre to be used by the Allocation Center and the INDO smart phone applications. A sample digital map in XML and its graphical illustration are shown in Fig. 4.2 and Fig. 4.3 respectively.

- **Sensors -** The parking spot occupancy detection system is a wireless/wired sensor network that can provide occupation state of each parking spot in real time. Once a trigger in any parking spot state happens, the detection system instantly updates the Data Centre.
- **Data Centre -** Acts as the central database server for all system's components. It holds all the information from the Planner Software about the digital maps of the parking areas and the indoor building. This composes of floor plans, nodes and POIs geographical coordinates and distances between entrances/exits and POIs. In addition, the Data Centre is periodically updated by the Sensors and carries the parking resource statuses. The centre is continuously queried by the Allocation Centre for information on the resources utilisation and the building's digital maps, and is queried by the users' smart phones for the indoor navigation data.
- **Allocation Centre -** A web service that runs a MILP model that optimally and fairly assigns/reserves the cheapest parking spaces to the users in terms of total commuting time. The assignment is based on key variables that are the users' POIs destinations and the current resource utilisation. The centre

provides non stop parking allocation service to the users and is described in details in the next section.

- **INDO Application -** It is an Android application that allows a user to request a parking space allocation once he/she arrive his/her destination. Once a space is allocated, the application guides the user inside the parking lot to assist him/her in reaching the parking space. Following that, the parking space ID is stored in the application, such that the user can easily return to his/her car using indoor navigation. Inside the building, the application utilises the NFC/RFID hardware inside the smart phone to establish an indoor navigation process to guide the user from source to destination.

- **NFC/RFID Tags-** NFC and RFID are wireless technologies for short range and long range communications respectively. In this system, the NFC or passive RFID tags are encoded with a unique electronic product code (EPC) that corresponds to a particular node, or in other words, a specific x,y coordinates. When the users' smart phones read the tags, the location of the users are instantly known. This allows the users to use the indoor navigation feature inside the INDO Application to reach their destinations. The EPCs are automatically generated in the Planner Software, then encoded using a NFC/RFID encoder printer.

4.3 Indoor Guidance and Navigation

Cell of Origin (COO) is originally a mobile positioning technique for locating the cell's location at which a device is originating a call. In mobile positioning, the accuracy is dependent on the number and location of the base stations, but in the common case, it exceeds the 100 meters. In this work, the COO technique is adopted, however instead of using base stations, very cheap RFID or NFC tags are used.

```xml
<?xml version="1.0" encoding="utf-8"?>
<Build>
   <Buildname>Mega Mall</Buildname>
   <DBServer>localhost</DBServer>
   <DBUID>AmirKotb</DBUID>
   <DBPass>root</DBPass>
   <DBName>trackingdb</DBName>
   <Location>XY</Location>
   <Totalblocks>1</Totalblocks>
<TotalNodes>43</TotalNodes>
<TotalPOIs>144</TotalPOIs>
<TotalDeletedNodes>0</TotalDeletedNodes>
<BlockList>
<Block>
   <BF>1,Floor,0,Block,A</BF>
   <BS>0.681348010160881</BS>
   <DPI>100</DPI>
   <MTS>360</MTS>
   <PPM>8</PPM>
</Block>
</BlockList>
<Allnodes>
<Node>
   <Name>E3</Name>
   <BLOCK>1</BLOCK>
   <Nodestatus>True</Nodestatus>
   <NID>3</NID>
   <Type>0</Type>
   <X>53</X>
   <Y>132</Y>
   <Xp>0.0658385093167702</Xp>
   <Yp>0.234875444839858</Yp>
   <FloorID>0</FloorID>
   <Floor>0</Floor>
   <Fad>BlockA</Fad>
<RGID>

<RFID>
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   <R_Accuracy>3</R_Accuracy>
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</RGID>
<Linkednodes>
<LIN>
   <L_ID>1</L_ID>
   <L_Name>E4</L_Name>
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   <L_Type>0</L_Type>
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   <L_StartNodePointY>132</L_StartNodePointY>
   <L_EndNodePointX>54</L_EndNodePointX>
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   <P_Yp>0.197508896797153</P_Yp>
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   <P_Function>0</P_Function>
   <P_Occupier />
   <P_Direct>162</P_Direct>
   <P_Distance>862</P_Distance>
</POI>
```

Figure 4.2: Digital map generated automatically by the Planner Software.

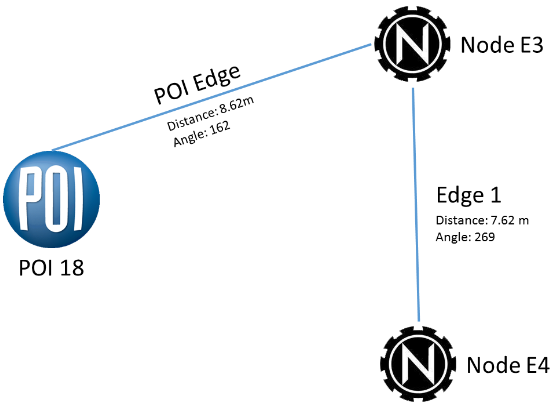


Figure 4.3: Graphical illustration of a Node-POI and Node-Node connections.

Most of the current smart phones are equipped with NFC reader which allows the application layer to retrieve or modify a NFC tag's ID. Similarly, a smart phone equipped with RFID reader can encode and decode a RFID tag. As mentioned earlier, the Planner Software links a tag's ID to a specific location or point of interest on the building's maps. Now whenever the smart phone approaches a tag, the tag is going to be interrogated by either the NFC or the RFID reader, and the tag's ID will be read and sent to the application layer for further processing. In the application, the ID will be matched with a specific location using the information provided in the digital map.

The process starts by searching for or choosing a point of interest in the building. Following that, the user scans a NFC or RFID tag located at their location. At this point, the application retrieve the source and destination nodes by firstly locating the destination node ID at which the POI is linked to and secondly by retrieving the node ID from the user's location tag. In this application, the Dijkstra's shortest path algorithm is adopted to find the shortest route from source to destination. The path is then displayed to the user and the navigation process starts. Now whenever the smart phone detects a new tag, the location of the user is updated and if the tag's ID belongs to the set of IDs in the shortest path, the same path is used and the user is updated with the next directions information. On the other hand, if the tag's ID doesn't belong to the shortest path previously calculated, a new shortest path is going to be calculated and a new route will be displayed to the user. This process ends when the user reach their destination. In addition to the graphical navigation directions, voice directions are also provided to enhance the navigation experience. The application also categorises the POIs based on their type. Such that a user can search for a POI by its name, type or occupant's name.

The RFID tag deployment is an important factor that decides the efficiency of the system. Since the accuracy of the positioning system is based on the reader-tag reading range, it is a very flexible yet a cost effective system. In general, 5 meters

Table 4.1: Passive UHF RFID tag benchmarks

Tag	R **(m)**	**Reading Side**	**Background Type**
Omni ID Dura 3000	25	Front	On||Off-metals
Alien G-Tag	5	Front/Rear	Off-metals
Xerafy Cargo Trak	3	Front/Rear	On||Off-metals
Omni ID Dura 1500	2.5	Front/Rear/Sides	On||Off-metals
Omni ID Exo 750	1.5	Front/Rear	On||Off-metals
Xerafy Micro	1	Front/Rear/Sides	On||Off-metals

R is the practical measured reading range. The reading side and background type information assist in the tag deployment process.

accuracy is sufficient for indoor guidance inside buildings like shopping malls. This can be achieved using UHF RFID passive tags that are commercially available and they provide a reading range starting from few centimeters up to 30 meters. Since the RFID tags requires no line of sight, they could be placed on the ceilings, the ground or the sidewalls. In Table 4.1, common RFID tags with their respective read ranges and types are shown to assist in the tags deployment process. On the other hand, the NFC tags have the read range of few centimeters and hence they must be deployed in areas that can be reached by the building visitors, so they can tap it with their smart phones.

4.4 Parking Resource Allocation

The objective of our MILP model is to minimise the total commuting time for all users. We will formulate our model based on the queuing model in Fig. 4.4. There are N spaces that are split into normal $\mathbb{P}1$ and disabled $\mathbb{P}2$ spaces. The running time of the allocation centre is discretized into small time periods. We will denote each

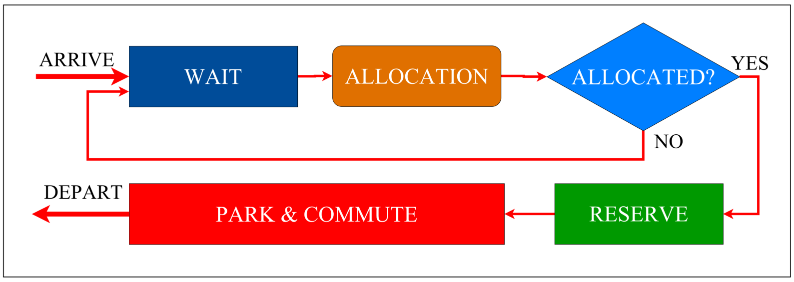


Figure 4.4: Queuing model flow.

time period as a decision point K. All users arrive to the allocation center randomly and independently join the WAIT queue. At each decision point, the allocation centre will allocate resources to users and move them to the OCCUPY queue. Notice here that if a user enters the OCCUPY queue, that doesn't imply for granted that the user has physically occupied a parking space, instead the space will be treated as reserved until the user physically occupies it. When users either get allocated or depart the parking spaces, the states of the parking spaces are going to be updated instantly.

4.4.1 Problem Formulation

At each decision point K, we will define the state of the allocation system $A(K)$ and the state of users $X_i(K)$ as follows:

$$A(K) = \{W(K), O(K), Z(K)\} \tag{4.1}$$

$$X_i(K) = \{l_i(K), \upsilon_i(K), \mathbb{F}_i(K)\} \tag{4.2}$$

We will use the following definitions to describe the allocation and users' state:

- $W(K)$ = {i: user i is in WAIT}
- $O(K)$ = {i: user i is in OCCUPY}
- $Z(K)$ - describes the number of vacant resources.
- $l_i(K)$ - describes the location of user i.

- υ_i - is the occupied resource j by user i.
- $\mathbb{F}_i(K)$ - is the set of feasible resources that user i can park in.
- $\mathbb{D}_i$ - is the chosen destination d by user i.
- $C1_j$ - is the driving distance from the entrance of the car park to the resource j.
- $C2_{gj}$ - is the walking distance from the resource j the gate g.
- $C3_{gd}$ - is the walking distance from the gate g to the destination d.
- $C4_j$ - is the driving distance from the resource j to the exit of the car park.
- $CMax$ - is the maximum commuting time throughout the park and the building.

Below, some key binary variables are defined:

$$\varphi_i = \begin{cases} 1, & \text{if } i \text{ is requesting a normal resource} \\ 0, & \text{if } i \text{ is requesting a disabled resource} \end{cases} \tag{4.3}$$

$$Sj(K) = \begin{cases} 1, & \text{if } j \text{ is a vacant resource} \\ 0, & \text{if } j \text{ is a occupied resource} \end{cases} \tag{4.4}$$

$$\beta_j = \begin{cases} 1, & \text{if } j \text{ is a normal resource} \\ 0, & \text{if } j \text{ is a disabled resource} \end{cases} \tag{4.5}$$

To reduce the problem complexity, $\mathbb{F}_i(K)$ will be defined as the set of feasible resources for every user i based on the resource's vacancy state and its type:

$$\mathbb{F}_i(K) = j : Sj(K) > 0, \varphi_i = \beta_j \tag{4.6}$$

By defining $VDrive$ and $VWalk$ as the driving and walking speeds respectively, the commuting times in driving and walking can be estimated as follows:

$$CDrive_j = \frac{C1_r + C4_r}{VDrive} \tag{4.7}$$

$$CWalk_{ijg} = \frac{2(C2_{gj} + C3_{gD_i})}{VWalk} \tag{4.8}$$

Now we can calculate the cost function $J_{ijg}(K)$ that we will minimise for user i. The cost function is a fraction from 0-1 representing the actual total commuting time as a percentage of the maximum possible commuting time.

$$J_{ijg} = \frac{CDrive_j + CWalk_{ijg}}{CMax} \tag{4.9}$$

4.4.2 Objective Function

We introduce the binary decision variable $x_{ijg}(K)$ such that

$$x_{ijg} = \begin{cases} 1, & \text{if user } i \text{ is assigned resource } j \text{ and gate } g \\ 0, & \text{otherwise} \end{cases} \tag{4.10}$$

and define matrix $X = [x_{ijg}]$. Now we can formulate the objective function and constraints for our problem that is solved at each decision point K:

$$\begin{aligned} minimise \sum_{i \in W(K)} \sum_{j \in \mathbb{F}_i(K)} \sum_{g \in Gates} x_{ijg}(K) \cdot J_{ijg}(K) \\ + \sum_{i \in W(K)} (1 - \sum_{j \in \mathbb{F}_i(K)} \sum_{g \in Gates} x_{ijg}(K)) \end{aligned} \tag{4.11}$$

s.t.:

$$\sum_{j \in \mathbb{F}_i(K)} \sum_{g \in Gates} x_{ijg}(K) \leq 1 \quad \forall i \in W(K) \tag{4.12}$$

$$\sum_{i \in W(K)} \sum_{g \in Gates} x_{ijg}(K) \leq 1 \quad \forall j \in \mathbb{F}_i(K) \tag{4.13}$$

$$\begin{gathered}(\sum_{n\in\mathbb{F}_i(K)} x_{mng}(K)) - x_{ijg}(K) \geq 0 \\ \forall i,m \in W(K), j \in \mathbb{F}_i(K), g \in Gates \\ s.t.\ \ \tau_m(K) > \tau_i(K), \varphi_i = \varphi_m\end{gathered} \tag{4.14}$$

The objective function in (4.11) can be split into 2 parts, $\sum_{i\in W(K)}\sum_{j\in\mathbb{F}_i(K)}\sum_{g\in Gates} x_{ijg}(K)\cdot J_{ijg}(K)$ and $\sum_{i\in W(K)}(1-\sum_{j\in\mathbb{F}_i(K)}\sum_{g\in Gates} x_{ijg}(K))$. In this problem we minimise the objective function and this will have two effects according to the mentioned parts. The first part aims to minimise the total commuting cost in (4.9) for all parkers in $W(K)$, such that user i will be assigned the resource j in his/her feasible resources $\mathbb{F}_i$ and gate g with the least J_{ijg}. If we did not add the second part to the equation, the system will not allocate any users by setting all $x_{ijg}(K)$ to zero. Therefore we introduce the second part to allocate as much users as possible in the $W(K)$. Resource allocation will be maximised because J_{ijg} by its definition is less than 1, thus adding a cost of 1 to the objective function is satisfactory enough to guarantee maximum resource allocation.

The constraints in this problem can be described as follows:

- **Capacity -** 1) constraint (4.12) ensures that all users in $W(K)$ cannot be assigned more than one resource. Also it indicates that those users might not get allocated, *i.e.*, $x_{ijg}(K) = 0$. 2) constraint (4.13) indicates that the a vacant resource cannot get occupied by more than one user.
- **Fairness -** Constraint (4.14) indicates that if user i has arrived to the allocation system before the user m, such that $\tau_m(K) > \tau_i(K)$ and users i and m are requesting the same parking type, then a priority of allocation would be given to user i such that $x_{mjg}(K)$ must be set to 0 if $x_{ijg}(K)$=0.

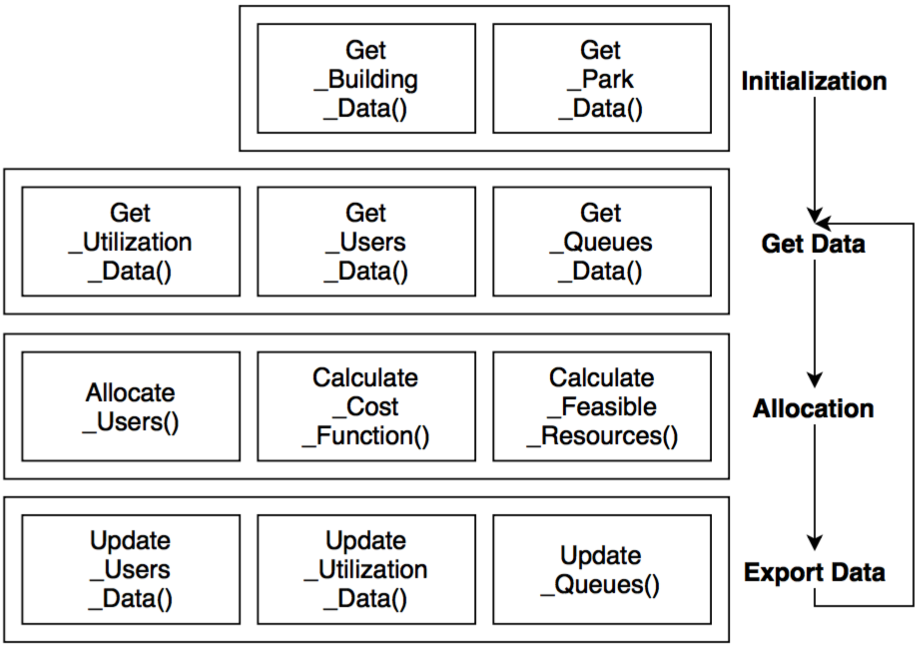


Figure 4.5: Program algorithm overview

4.4.3 Optimisation Algorithm

The software used to solve the MILP problem is IBM ILOG CPLEX (CPLEX). In order to evaluate the system effectiveness, sets of users' data are first randomized using Microsoft Excel, such as arrival times, chosen destinations and the times to be spent at destinations. A database is then created to store the random data and act as the storage node for the CPLEX program. The CPLEX program that is shown in Fig. 4.5 inputs the random data generated earlier and updates the database after the users' allocation. Last, a C# program is used to execute the CPLEX program for multiple times - number of execution times is equal to the total simulation time (T) in minutes.

4.5 Results and Discussions

4.5.1 Performance Metrics

From the point of user's view, smart commuting should cost less, either in terms of money, walking distance, searching time or all. In this study we have focused on reducing the total commuting time for the users - in the parking process and the building' visit process. On the other hand, from the point of parking managers' view, parking resource utilisation and the service rate are of much interest. Thus we define the following main performance metrics:

- Utilisation - is the average resource utilisation and is calculated by dividing the total resource utilisation over the product of the number of parking spaces and the total simulation time.
- Commuting Time (CTime) - is the total time spent in driving and walking per user excluding the time spent inside the user's chosen destination, e.g., particular shop.
- Service Ratio - is the percentage of users who got allocated and occupied parking resources out of the total users who arrived to the allocation system throughout the simulation time.
- Wandering - is the ratio of users who arrived to the allocation system, however they could not find or get allocated an available parking resource instantly.

4.5.2 Simulations Setup

In this section, INDO system is denoted as Smart-Commuting (SC), guided system as (G) and non guided as (NG1) and (NG2), respectively. G is modeled to be a smart commuting system without the parking resource allocation feature available in SC, such that a G user will blindly search for a vacant parking space but will have the indoor guidance feature to commute throughout the indoor buildings. On the other side, NG users will blindly search for vacant parking space and also blindly locate their destinations inside the indoor buildings without any assistance. The difference between the NG models are in the simulation and calculation of the walking cost or the route planning inside the indoor buildings, such that for NG1, the users inside the building are going to take a path to their destination that has a cost of the average of all possible direct paths. Whereas for NG2, the users inside the building are going to take a path to their destination that is random in terms of cost between the shortest possible path and the one of the longest path.

Parking behaviour for the G, NG1 and NG2 are similar, such that users would scan the parking area in a sequential order until they find vacant spaces (See Appendix D for more information about G, NG1 and NG2 parking methodology). Then they would enter the building from the nearest gate. At the end of the process, the users will find the nearest exit.

In all the simulations, the user arrivals to the allocation system are assumed to be Poisson distributed with rate λi. The arrival rates are varied from low arrival rate ($\lambda = 3$) to high arrival rate ($\lambda = 12$) to analyse the performance of INDO over guided and non guided systems. Times spent by users in their destination are exponentially distributed with the rate of 30 minutes. The users chosen destinations are random and uniformly distributed. For simplicity, a constant decision interval is adopted, such that, $T(K)$= 1400 minutes, K=1,2,... All the models are written in IBM ILOG CPLEX - a common commercial MILP solver software, all the logic are computed in C# and finally the results are stored in a MSACCESS database.

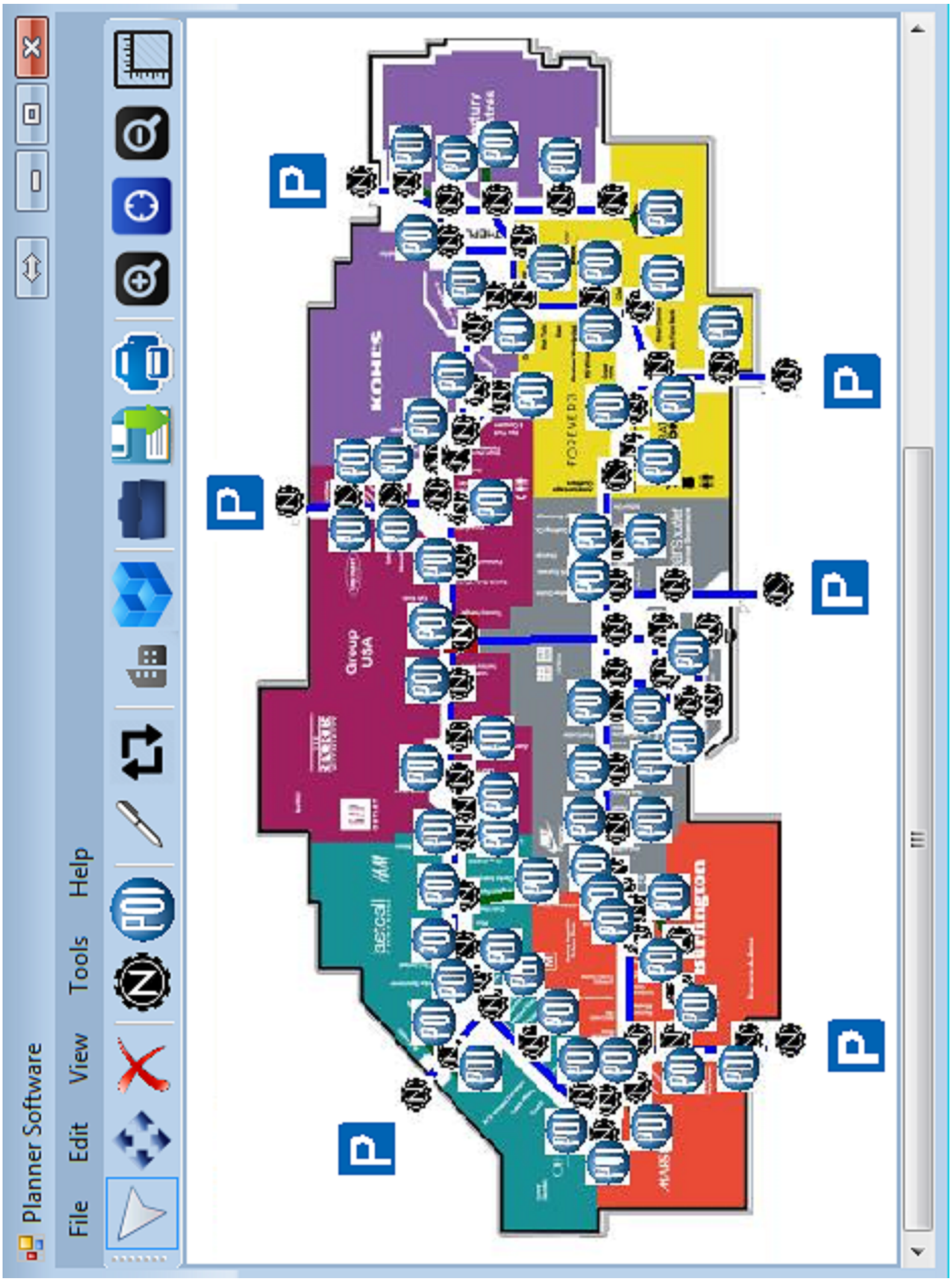
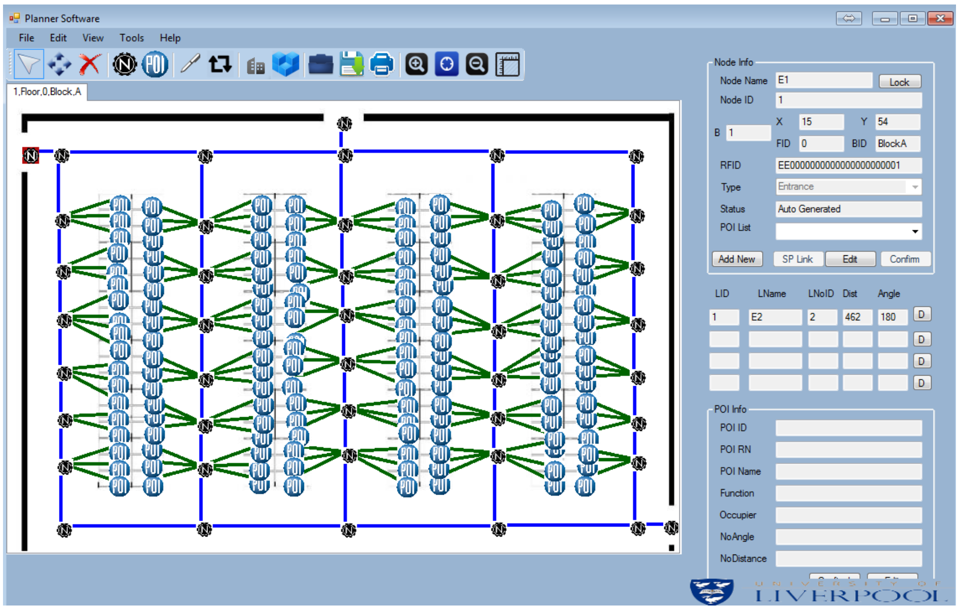


Figure 4.6: Case study environment: indoor map



Node Name: E1
Node ID: 1
B: 1
X: 15
Y: 54
FID: 0
BID: BlockA
RFID: EE0000000000000000000001
Type: Entrance
Status: Auto Generated
POI List:

LID	LName	LNoID	Dist	Angle
1	E2	2	462	180

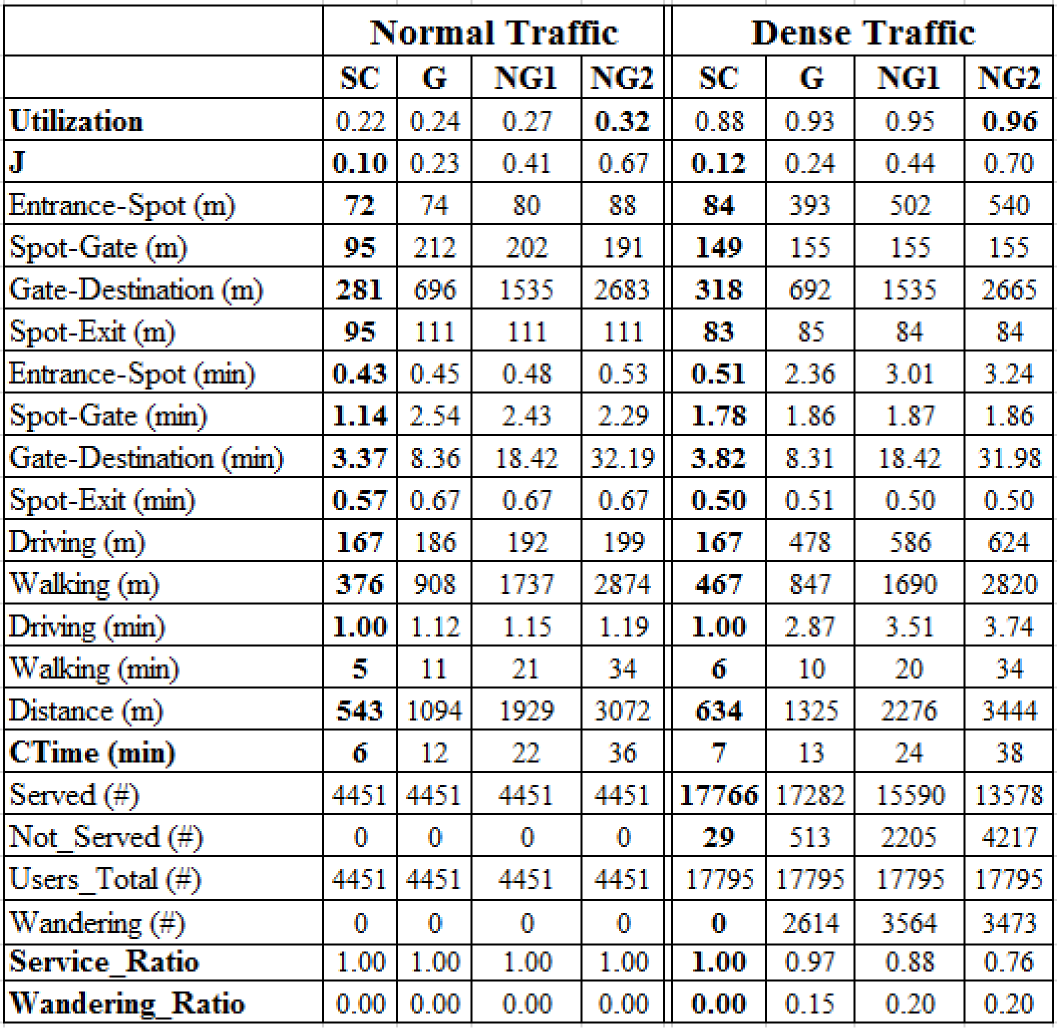
POI ID:
POI RN:
POI Name:
Function:
Occupier:
NoAngle:
NoDistance:

Figure 4.7: Case study environment: park map

4.5.3 Simulations Results

The results in Table 4.2 prove the concepts behind our system. From the user's point of view, SC proven to provide the user the lowest possible cost. In both normal and dense traffic, the cost *J* or the total commuting time is reduced by about 70%, 80% and 50% as compared to NG1, NG2 and G respectively. This result indicate the merits of both components of the INDO system - the indoor guidance and the parking allocation. The indoor guidance component alone of SC does significantly reduce the cost as compared to NG1 and NG2 by about 50% and 20% respectively. This is calculated based on the fact that G is similar to SC except that it doesn't provide the parking allocation component which results in a 10% of cost difference. The parking allocation component does not only reduce the driving time in the parking areas, it also contributes in the reduction of the walking time inside the building, since the allocation model allocates to the users the parking spots that are the nearest to the building's entrance that is also nearest to the final destination. This effect can be

Table 4.2: System performance during low and dense traffics



	Normal Traffic				**Dense Traffic**			
	SC	**G**	**NG1**	**NG2**	**SC**	**G**	**NG1**	**NG2**
Utilization	0.22	0.24	0.27	**0.32**	0.88	0.93	0.95	**0.96**
J	**0.10**	0.23	0.41	0.67	**0.12**	0.24	0.44	0.70
Entrance-Spot (m)	**72**	74	80	88	**84**	393	502	540
Spot-Gate (m)	**95**	212	202	191	**149**	155	155	155
Gate-Destination (m)	**281**	696	1535	2683	**318**	692	1535	2665
Spot-Exit (m)	**95**	111	111	111	**83**	85	84	84
Entrance-Spot (min)	**0.43**	0.45	0.48	0.53	**0.51**	2.36	3.01	3.24
Spot-Gate (min)	**1.14**	2.54	2.43	2.29	**1.78**	1.86	1.87	1.86
Gate-Destination (min)	**3.37**	8.36	18.42	32.19	**3.82**	8.31	18.42	31.98
Spot-Exit (min)	**0.57**	0.67	0.67	0.67	**0.50**	0.51	0.50	0.50
Driving (m)	**167**	186	192	199	**167**	478	586	624
Walking (m)	**376**	908	1737	2874	**467**	847	1690	2820
Driving (min)	**1.00**	1.12	1.15	1.19	**1.00**	2.87	3.51	3.74
Walking (min)	**5**	11	21	34	**6**	10	20	34
Distance (m)	**543**	1094	1929	3072	**634**	1325	2276	3444
CTime (min)	**6**	12	22	36	**7**	13	24	38
Served (#)	4451	4451	4451	4451	**17766**	17282	15590	13578
Not_Served (#)	0	0	0	0	**29**	513	2205	4217
Users_Total (#)	4451	4451	4451	4451	17795	17795	17795	17795
Wandering (#)	0	0	0	0	**0**	2614	3564	3473
Service_Ratio	1.00	1.00	1.00	1.00	**1.00**	0.97	0.88	0.76
Wandering_Ratio	0.00	0.00	0.00	0.00	**0.00**	0.15	0.20	0.20

observed by comparing the walking distance of SC and G, for example, SC is about 5 minutes less than G.

It is observed that the users' cost does show negligible changes in normal and dense traffic. The reason of this is that the walking time inside the building does in fact count as a minimum of 90% of the total user cost in all cases, and in reality, the number of people inside a building does usually cause negligible effect on their walking speeds. However, in dense traffic, the driving time increases by 150%, 205% and 210% for G, NG1, NG2 respectively as compared to their driving time in normal traffic. This increases are expected because in dense traffic the parking spaces get occupied much quicker than in normal traffic, thus the possibility of wandering around is much higher. For instance, the ratio of wandering users in dense traffic in G, NG1 and NG2 are 15%, 20% and 20% respectively. Whereas it is 0% for all systems in normal traffic. Now looking at SC, the driving time is identical in all scenarios of traffic due to the fact that users didn't wander around as the total commuting time is reduced in general which means that parking spaces are going to get vacant for new users much quicker as compared to the G and NG systems. It is important to notice that the previous results didn't include the users who were not served - the users who found no vacant spaces at all. The non served users are 3%, 12% and 24% of the total users for G, NG1 and NG2 respectively. Whereas 100% of the users were served in SC.

On the other hand, from the point of view of the building and parking management, SC provides 100% of service ratio as compared to 97%, 88% and 76% for the G, NG1 and NG2 respectively in dense traffic. This implies that in general in SC, more users are always going to be served. This in turn will significantly maximise the revenue especially in the cases of shopping malls, museums, etc.. The main drawback observed is the lower parking resource utilisation in SC as compared to others especially in lower traffic - 2%, 5% and 10% lower than G, NG1 and NG2 respectively. This is expected to happen when the users' commuting time gets

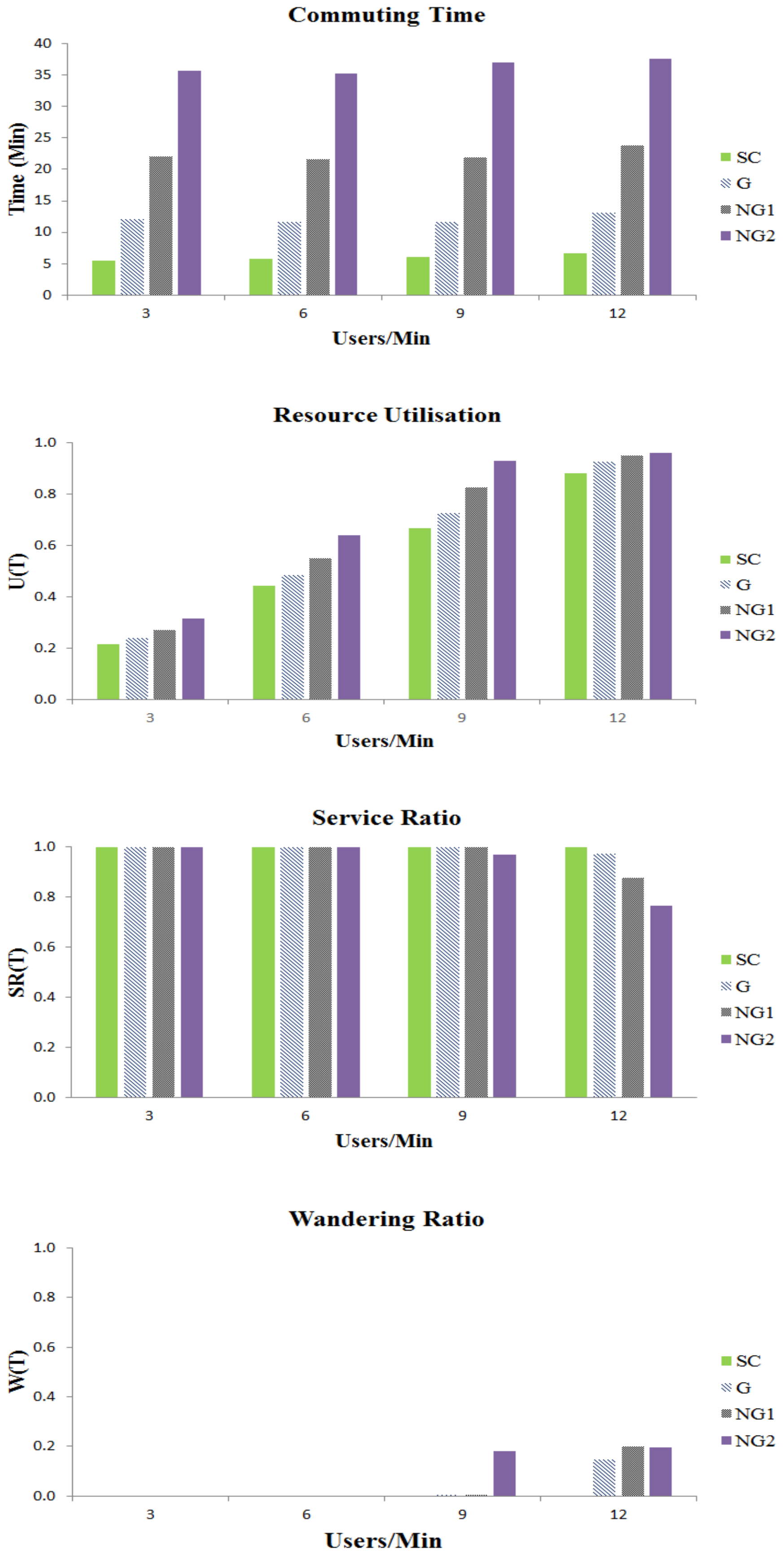


Figure 4.8: Performance metrics under different arrival rates.

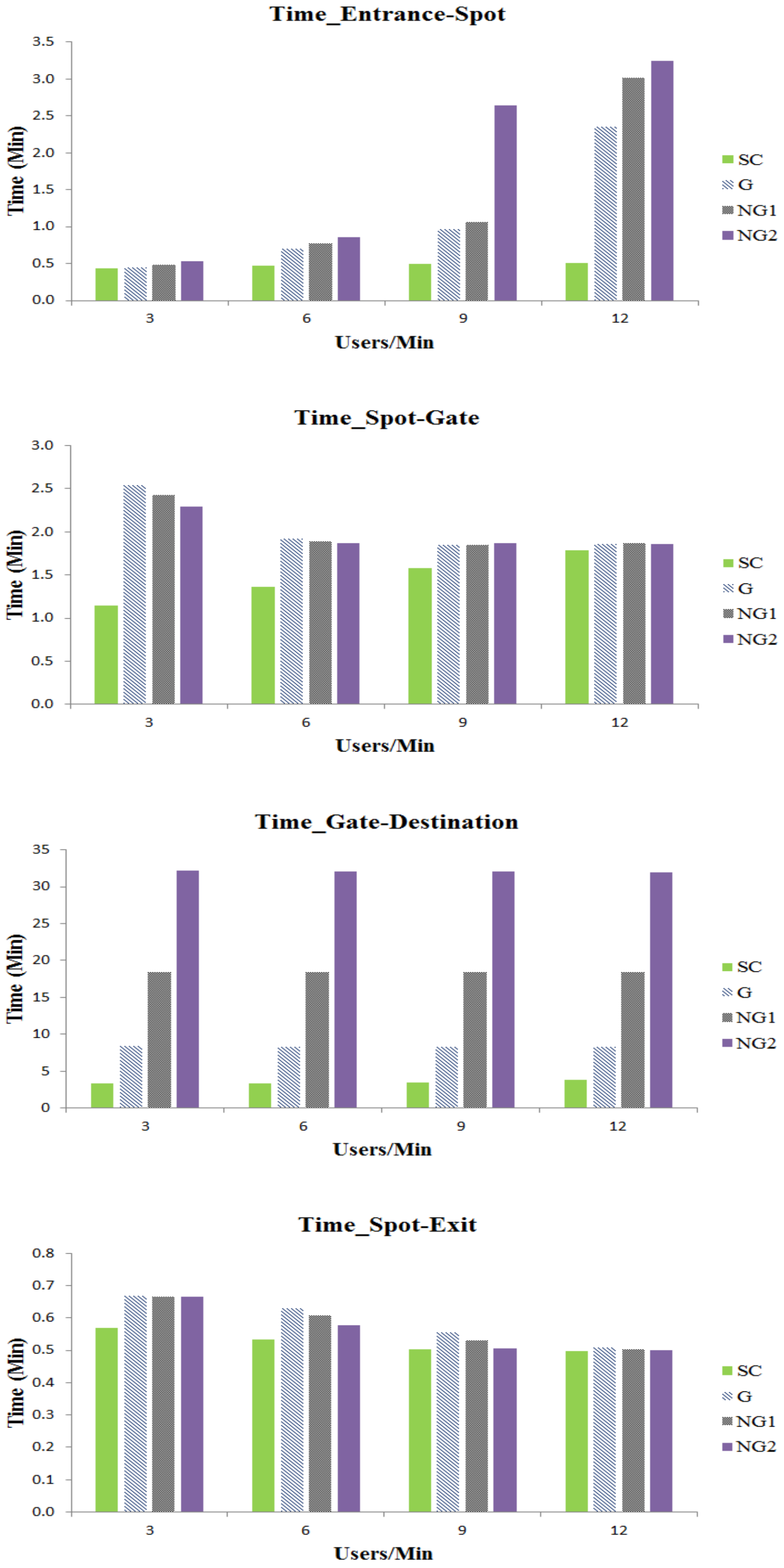


Figure 4.9: Cont. performance metrics under different arrival rates.

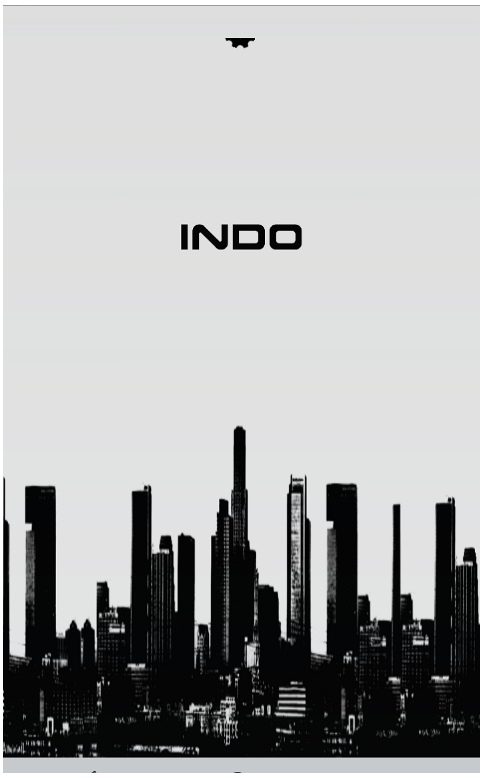


Figure 4.10: Launch window

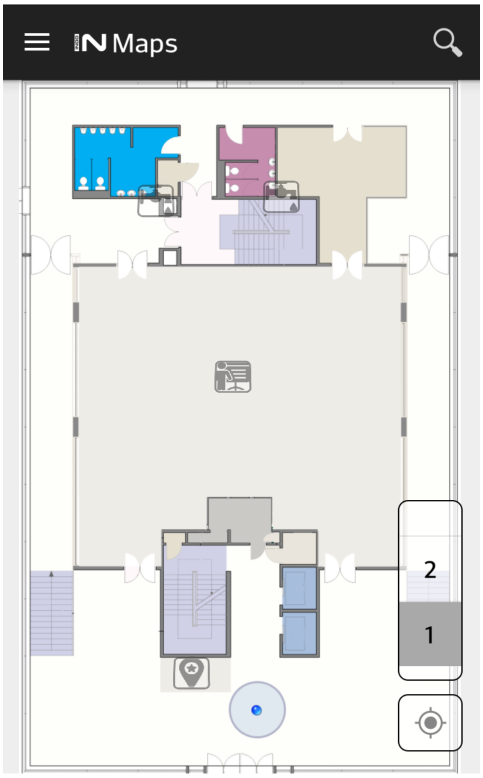


Figure 4.11: Main window

reduced in SC. However, this will not become a disadvantage for the case when parking is provided for free, and this is usually the case for the shopping malls.

By simulating all the four models under different arrival rates, additional simulation results are obtained and shown in Fig. 4.8 and Fig. 4.9 where they confirm the earlier discussion.

4.6 Implementation

The indoor guidance and navigation component of our system, as described in this chapter, has been developed and tested in the Electrical and Electronics Engineering department of the University of Liverpool. 102 tags were used to facilitate the navigation and guidance to 36 POIs found throughout 6 floors.

As discussed earlier, NFC and RFID tags (NFC: RapidNFC NTAG213 and RFID: Alien G-Tag) are affixed on the wall sides in known and accessible locations in the

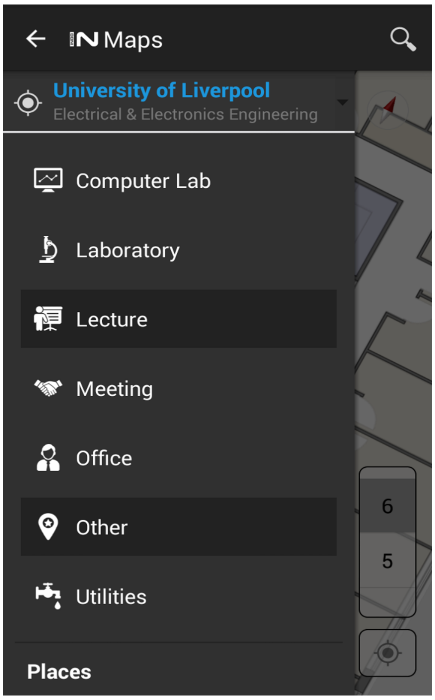
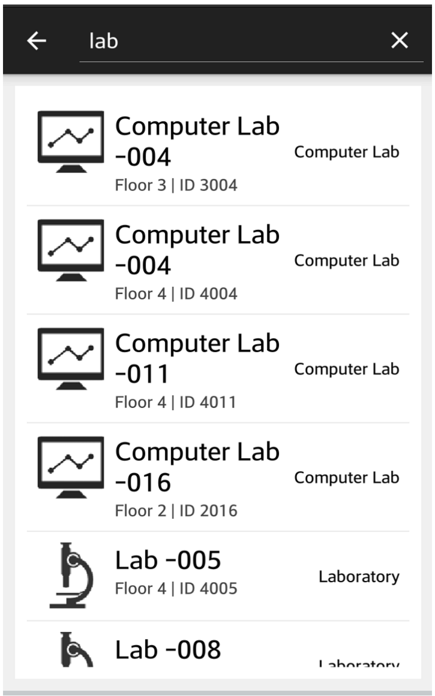


Figure 4.12: Layer selection window


lab

Computer Lab -004 Floor 3 | ID 3004	Computer Lab
Computer Lab -004 Floor 4 | ID 4004	Computer Lab
Computer Lab -011 Floor 4 | ID 4011	Computer Lab
Computer Lab -016 Floor 2 | ID 2016	Computer Lab
Lab -005 Floor 4 | ID 4005	Laboratory
Lab -008	Laboratory

Figure 4.13: Search window

buildings. Once the user's device scans a tag, the digital map of the building is identified and the application starts as show in Fig. 4.19 loading that map (if the map is not stored on the phone, it will be downloaded from the INDO server). By swiping the screen from left to right, a list menu will appear as shown in Fig. 4.12, where the selection of POI types can be made, e.g., lecture rooms, toilets, etc.. Upon selection of any of the layers, that particular POI type icons will be displayed or removed from the top layer of the graphical user interface (GUI). This application features an easy and user friendly to use GUI, such as the drag, zoom and rotate functions using finger gestures.

To find a destination, the user can use the Search window as shown in Fig. 4.13 using text or voice, by pressing the search button of the application top bar. Using a single search interface, the user can find a place by its name, type or floor ID. Alternatively, the Places window can be used to find a place by exploring the POI types as shown in Fig. 4.14. When any type is selected from the list, all the POIs

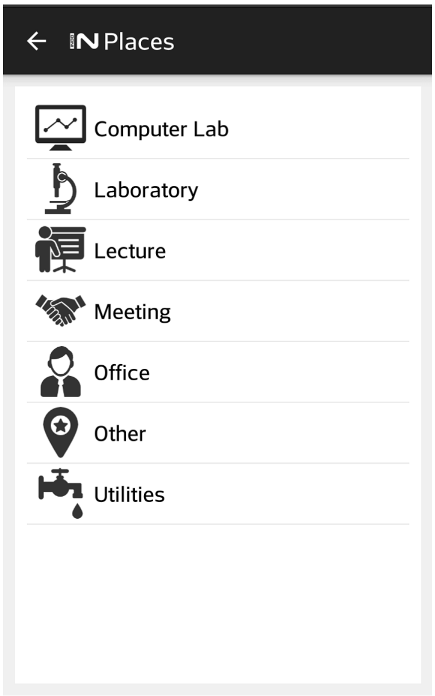


Figure 4.14: Places window

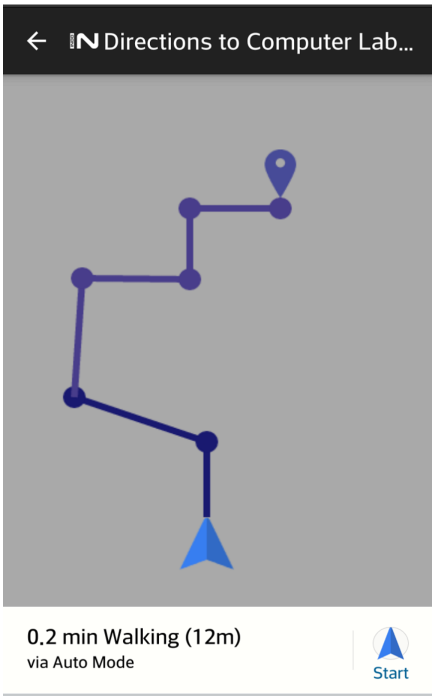
Computer Lab -004
Computer Lab

Figure 4.15: POI icon and information

with this type will be listed to the user. Last method is by selecting the POI icon found on the POI layer in the main window.

On the selection of any of the POIs, the name and type of the POI is displayed to the user as in Fig. 4.15. When the user presses on the directions button, a new window displaying the graphical representation for the source-destination directions is displayed as in Fig. 4.16. At the bottom of this window, a summary of the journey is showed to the user including the total distance and time to the destination and also the routing mode (auto, stairs and lift), which can be modified in the settings window. The visual directions are shown over a blank background such that the nodes and links from user's current floor is in different color than the rest of other nodes and links in other floors. Furthermore, when the user swipes the bottom window to the top, written directions would be showed as in Fig. 4.17.

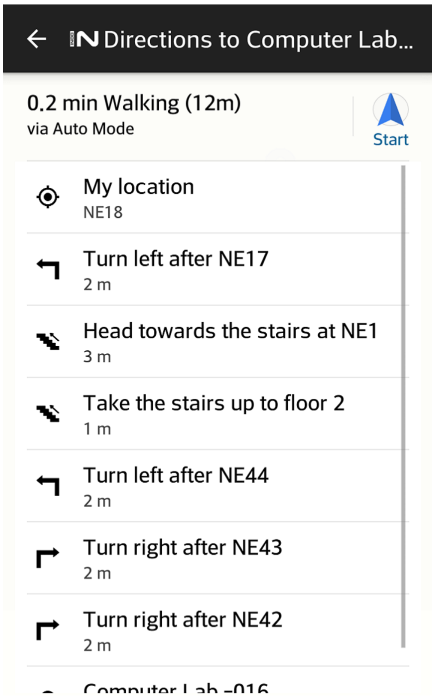
Now when the user presses the start navigation button, the navigation window launches showing the current position and the directions to the last node in the user's



Directions to Computer Lab...

0.2 min Walking (12m)
via Auto Mode

Figure 4.16: Visual directions



Directions to Computer Lab...

0.2 min Walking (12m)
via Auto Mode

My location
NE18

Turn left after NE17
2 m

Head towards the stairs at NE1
3 m

Take the stairs up to floor 2
1 m

Turn left after NE44
2 m

Turn right after NE43
2 m

Turn right after NE42
2 m

Computer Lab -016

Figure 4.17: Written directions

current floor as depicted in Fig. 4.18. In addition, written instructions are shown to the user at the top of the Navigation window, including next node name, current floor ID, distance to next node and the direction instruction. The user can also manually navigate through their next directions in the route for offline use. The navigation widow is tilted to simulate a 3D navigation experience and voice instructions are produced to enhance the navigation experience.

4.7 Conclusions

In this chapter we have proposed INDO, a new smart indoor commuting and car parking system which is based on MILP model that yields optimal solution for allocating parking spaces to users - providing the least cost in terms of total commuting time. The new concept introduced here is the combination of resource allocation and the indoor navigation and guidance. The parking and commuting processes for our system, guided and non guided systems have been modeled and evaluated. Our

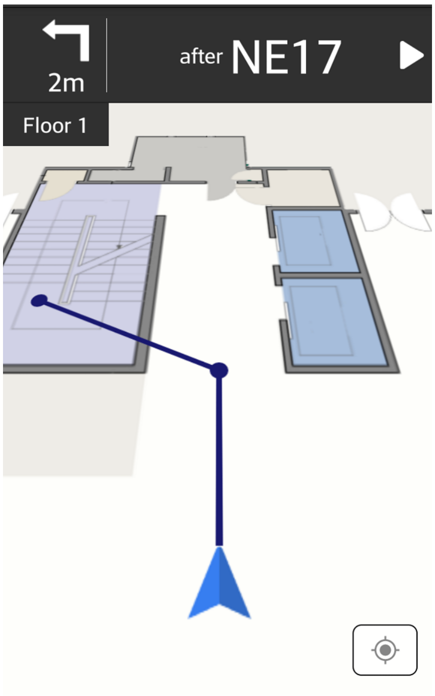
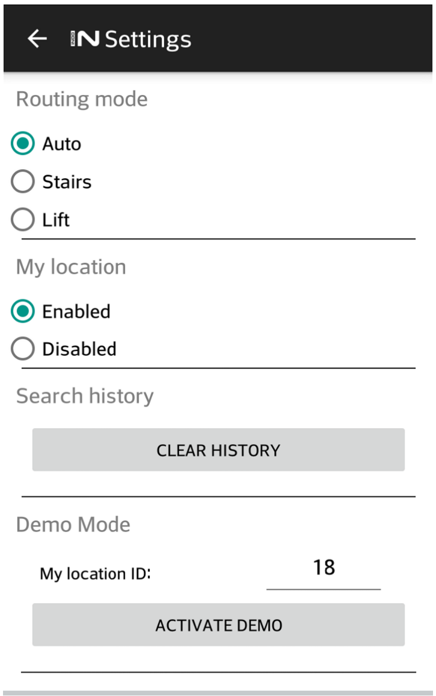


Figure 4.18: Navigation window



Routing mode

● Auto
○ Stairs
○ Lift

My location

● Enabled
○ Disabled

Search history

Demo Mode

My location ID: 18

Figure 4.19: Settings window

simulation results indicate a significant reduction in the total commuting time by 30% to 60% as compared to unguided systems. Furthermore, the resource allocation component in our system have shown a 10% reduction in commuting time as compared to guided systems - that features indoor navigation and guidance only.

On the other hand, our system maximises the service ratio in dense traffic, such that the parking areas can serve more arriving users as compared to the guided and non guided systems. Finally, a software package was developed and the system implementation was discussed. INDO is an intelligent component of a smart city concept. In fact, it could be utilised not only to save time for the users, but it can serve other parties such as targeted advertisement, marketing, tracking and knowing user habits.

Chapter 5

‘RFPark’ - A Spot Occupancy Detection System Using Passive UHF RFID

5.1 Introduction

In this chapter, a new approach for parking monitoring using an Ultra High Frequency (UHF) Radio Frequency Identification (RFID) based system is proposed. This system works by deploying passive RFID tags on the asphalt and an array of RFID readers across the parking area. When the parking spaces are vacant, the RFID readers will interrogate the tags and read their unique Electronic Product Codes (EPCs) that correspond to the parking spaces identifications. In contrast, when a vehicle occupies a parking spot, the reader will fail to receive the signal from the tag below the vehicle knowing that this particular spot is occupied.

As opposed to the sensor-based systems, this approach could overcome many of their problems. For instance, the RFID system is immune to weather conditions and gravity. In addition, the RFID tags are passive and require no power lines nor batteries that require frequent replacements. Furthermore, a wireless sensor network

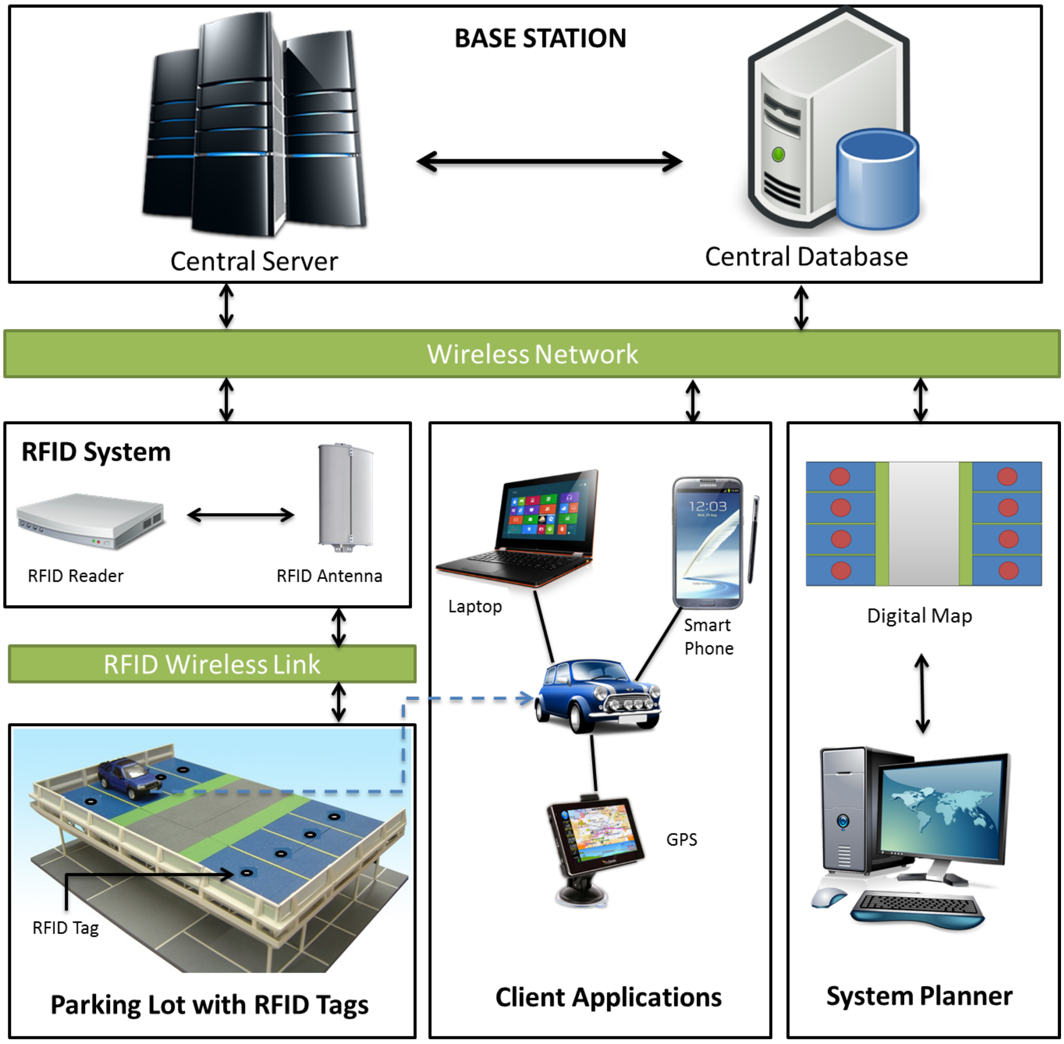


Figure 5.1: System framework overview.

consists of sensors and RF transceivers. Whereas, the RFID tag in our approach act as a sensor and RF transceiver at the same time. On the other hand, the RFID approach overcomes the main challenge of the image based method, which is the sensitivity to light intensity and weather conditions. Hence, it could be more cost effective, easier to install and require much lower maintenance.

5.2 'RFPark' System Framework

UHF radio waves have a shorter wavelength as compared to high frequency (HF) and low frequency (LF) radio waves. As a consequence, their signals are more likely to attenuate and they cannot penetrate through fluids or metals. Because vehicles contain a great portion of metals, it is certain that UHF RFID readers, with antennas placed above vehicles, will fail to interrogate the UHF RFID tags placed on the ground below vehicles, e.g. on the asphalt. Now by assigning unique EPCs to these tags that identify the parking spaces, a spot will be known to be vacant if its corresponding tag is read and known to be occupied if otherwise. In this section, the architecture of the detection system is discussed along with the methodology behind selecting the appropriate reader and tag pair.

5.2.1 Architecture

The main components of the RFID detection system are described as follows:

- **RFID Reader -** The reader in this work is responsible for interrogating the surrounding tags and periodically sending reports to the base station. A report that is produced by the embedded software inside the RFID reader contains read tags information like EPC, timestamp, received signal strength indicator (RSSI), frequency and RF phase. A typical fixed RFID reader can be connected to multiple antennas by coaxial cables and to the internet through Ethernet or Wi-Fi. Some commercial RFID readers are able to overcome the RF interference using frequency hopping technique, allowing the deployment of an array of fixed readers and antennas in the same area.

- **RFID Tag -** A RFID tag is deployed on the asphalt in the middle of a parking spot. Each RFID tag is programmed with a unique EPC. The EPC is generated automatically by the Planner Software, such that it represents a unique parking spot. In this work, we utilise Passive UHF RFID tags for their ability to operate without batteries and for long distances. When radio waves from the RFID reader are encountered by the tag, the coiled antenna within the tag forms a magnetic field. The tag draws power from it, energizing the circuits in the tag.

The tag then sends the information encoded in the tag's memory - the EPC - to the RFID reader antenna using the back-scattering principle.

- **Base Station -** It could be a cloud-based or PC-based. In both cases, the base station will contain 2 active services. The first is called Central Server (CS) which is responsible for Hypertext Transfer Protocol (HTTP) listening to incoming reports from all the RFID readers. On receipt of each report, the CS will process the data and update the Central Database accordingly. In addition, the CS also listens for HTTP GET commands from client applications and update them with parking information. The second service is the Central Database which stores the information about parking IDs, parking times and parking availability.
- **Client Applications -** Two client applications act as the graphical user interfaces (GUIs), the first runs on a windows PC and the second is a smart phone application running on Android platform. Both client applications allow the users to choose a parking lot and view the occupancy status of all the parking spots in real time. The communication is done via HTTP POST and HTTP GET methods.
- **System Planner -** It is a Windows based program that converts a parking layout map into a digital map that the system can interpret. The process starts by importing the layout images of the parking area into the program. Following that, the administrator inserts nodes at the desired locations of the RFID tags for each of the images, then upload the digital map to the central database. A node carries the information for the EPC, the reader ID, the antenna ID and the location information of its corresponding RFID tag. As shown in Fig. 5.2, a whole parking lot (either indoors or outdoors) is named grand zone and is split into parent zones. Each parent zone typically represents a parking area that is covered by one RFID reader with its antennas covering smaller child zones.

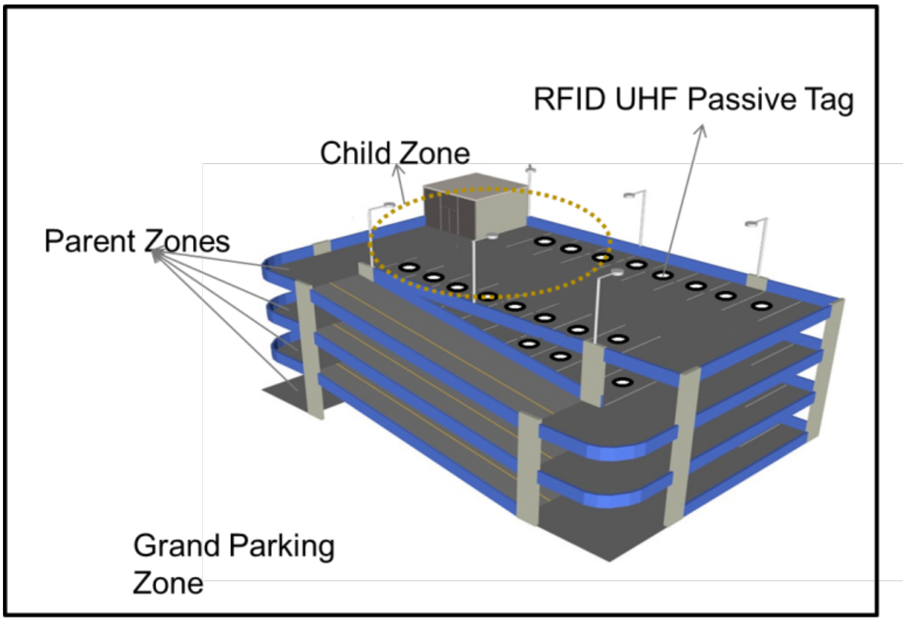


Figure 5.2: System planning: a parking lot is a ’grand zone’ having multiple sections- ’parent zones’. A parent zone is the zone covered by one RFID reader and is split into multiple child zones that are each covered by a RFID reader antenna.

5.2.2 RFID Reader and Antenna Selection

The requirements needed from the RFID reader are as following:

- **Flexible deployment:** RFID readers are typically either hand-held or fixed. Hand-held readers contain only one antenna and are used mainly in inventory missions at mobile locations. Whereas fixed readers can be connected to multiple antennas and generally speaking, they are much more powerful than hand-held readers in terms of technology and flexibility in antennas choice.

- **Maximum read range:** In order to deploy the RFID detection system with minimalistic hardware and to cover as many parking spaces as possible, the maximum read range is critic. The higher the gain of the reader antenna and the reader transmission power, the higher the read range. RFID reader performance is also measured by the sensitivity or the lowest RSSI the reader can detect.

- **RF interference immunity:** In principle, when multiple readers in close proximity of each other are interrogating tags at the same time, only one of the readers may succeed to read the tags. To overcome the interference, several communication protocols and methods have to be utilised, e.g. listen-before-talk method and frequency hopping. In commercial RFID readers, the dense reader mode is the technology that overcomes the RF interference problem.

In addition, the RFID reader should be able to provide low level data, such as RSSI readings. Based on the previous discussion, we have chosen the Impinj Speedway Revolution fixed RFID reader and the Liard circularly polarized 8 dBi antenna. This RFID reader is capable of transmitting at 0-30 dBm and receiving at as low as -70 dBm in the frequency band 860-960 MHZ. The Impinj reader also has the ability to interrogate RFID tags in several modes, including the dense mode. The Liard antenna when connected with the Impinj reader at 30 dBm can theoretically transmit radio waves at the effective radiated power (ERP) of 3 Watts in a 70 degrees beam width. Finally, the Impinj reader is rich with embedded software features that enable advanced and customized deployments.

Figure 5.3: Liard 8 dBi antenna and Impinj Speedway Revolution RFID reader.

5.3 Experimental Analysis and Results

In this section, the best RFID tag that suites our system is selected by performing RFID tag benchmarks on several RFID tags. Following that, the selected RFID tag together with the previously selected RFID reader and the RFID reader antenna are tested for maximum read-range measurement, both theoretically and practically. Last the RFPark system performance is analysed in an outdoor parking environment.

5.3.1 RFID Tag Benchmarks

It was obvious that current vendors of RFID tags publish limited performance data about their tags, e.g., maximum read range. However, the information they provide is not sufficient enough for the end users to allow them decide which tag to use in their application and how to deploy it. In this section we present how to conduct benchmark testing for any passive or semi passive RFID tag using simple resources and test metrics, while exploring and measuring the performance of a variety of RFID tags. This will eventually lead us to the choice of the RFID that best suites our RFPark system.

The evaluation of the performance of the tags in these measurements is based on the RSSI (Received Signal Strength Indicator) which is measured in dBm and this is an indication to the received power at the reader side from the tag.

5.3.1.1 Benchmarks Methodology

There are 5 experiments that have been applied on 8 different RFID tags (7 passive and 1 semi passive) and the setup of these experiments have been done in a anechoic chamber. The reader used in these measurements is Alien Handheld reader 9011, and the tags are from the manufacturers OMNI, Alien, Power ID, Metal Craft and Xerafy.

Default settings: In all the experiments, the RFID reader antenna and the Tag Under Test (TUT) were placed 1.5 meters above the ground. The RFID reader default transmission power was set to 30 dBm. All the supporting materials were made from wood and plastic to avoid any RF propagation reflections. Last, kitchen aluminum foil was used in the experiments where a metal effect measurement is needed.

- **Experiment A:** In this experiment, the RSSI from each TUT is observed while varying the distance between the RFID reader antenna and the TUT. First, the experiment is carried out with the TUT off metal and then repeated with the TUT attached to metal. The experiment is performed by fixing the TUT and vertically moving the RFID reader antenna towards the tag in a straight line (distance between the RFID reader antenna and the TUT is 7 meters). The RFID reader transmission power is kept fixed at 30 dBm.

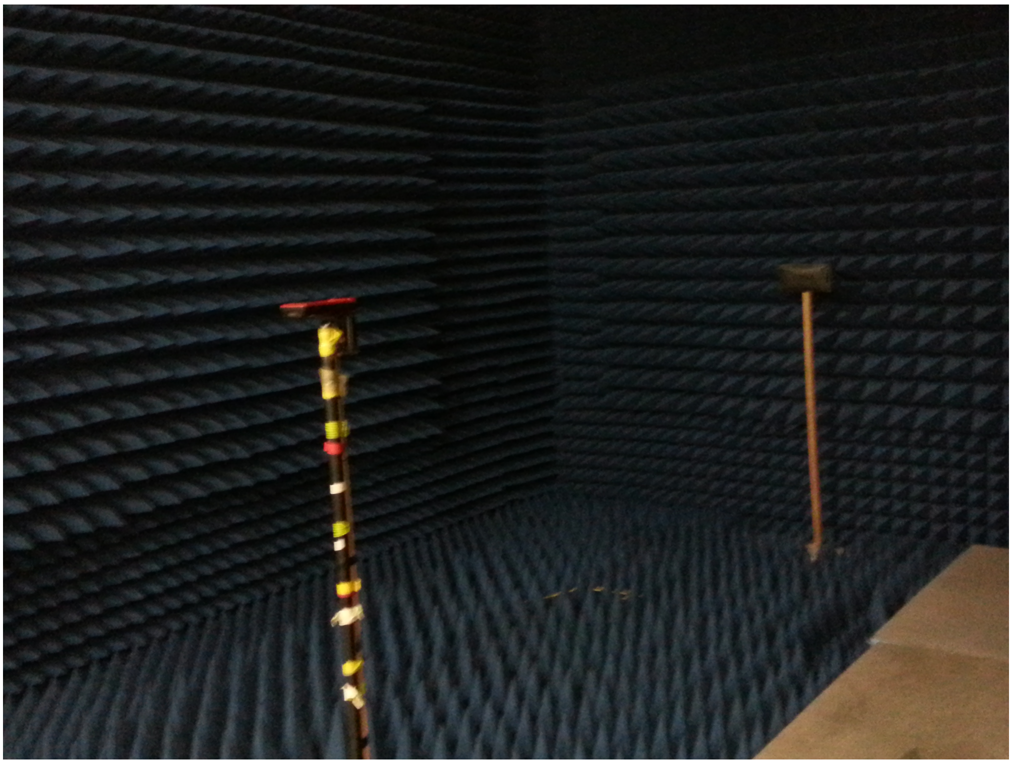


Figure 5.4: A picture taken during the anechoic chamber measurements.

- **Experiment B:** In this experiment, the maximum read range for a successful TUT reading is measured at the different variation of the RFID reader transmission power. The transmission power is varied from 30 dBm to 0 dBm on a 5 dB steps. To record a maximum read range, the TUT is fixed and the RFID reader antenna moves away vertically in a straight line until the TUT is not read by the RFID reader anymore. At this point, the maximum read range is recorded. The experiment is performed on and off metal.
- **Experiment C:** In this experiment, the minimum RFID reader transmission power needed to power the TUT - on and off metal - is measured while recording the RSSI. Initially, the RFID reader transmission power is set to -1 dBm - the lowest transmission power - and then the power is increased until a successful TUT reading happens. At this point, the RFID reader transmission power and the RSSI are recorded. The distance between the RFID reader antenna and the TUT is fixed at 1 meter.
- **Experiment D:** In this experiment, the radiation pattern of the TUT is measured. The RFID reader antenna is fixed at 0.5-2 meters away from the TUT. The TUT is then rotated 0-360 degrees on a 15 degree step. Following this measurement, the orientation of the TUT is varied from horizontal to 45 degrees to vertical. The radiation pattern is measured based on the RSSI.

5.3.1.2 Benchmarks Results

As observed in Fig. 5.5 and Fig. 5.6, the received signal strength is inversely proportional to the distance between the reader and the tag. Some tags which are optimised to work over metals gives triple the read range compared to if attached to non-metals and vice versa. However, some tags can have the same performance on and off metals. It is also important to note that tag E in Fig. 5.5 is a semi passive tag,

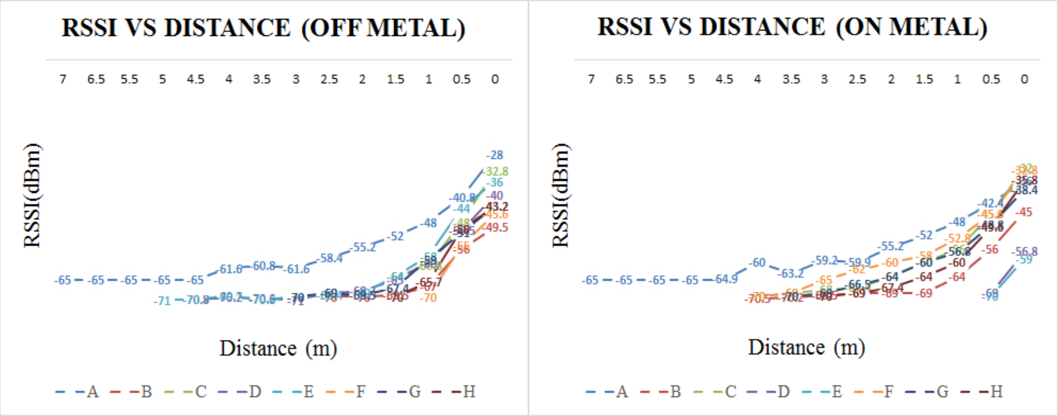


Figure 5.5: RSSI Vs. distance for RFID tags off-metal and on-metal.

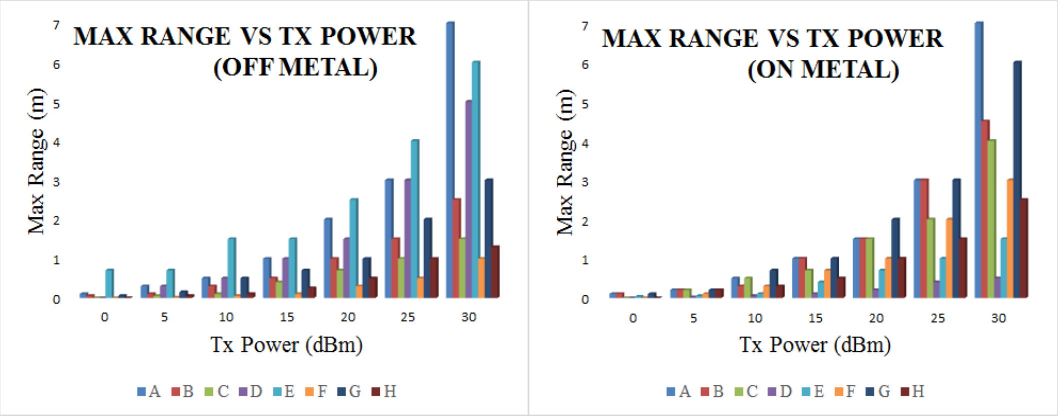


Figure 5.6: Max reading range Vs. RFID reader transmission power for RFID tags off-metal and on-metal.

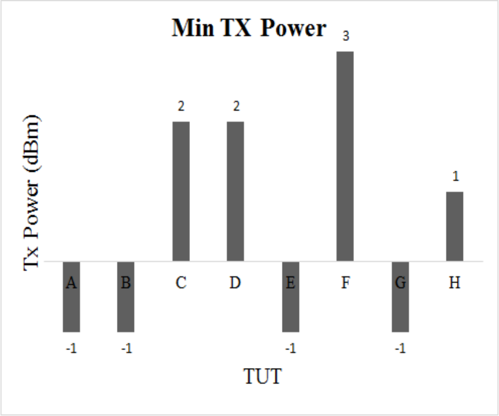


Figure 5.7: Minimum RFID reader TX power at 0.5 meter.

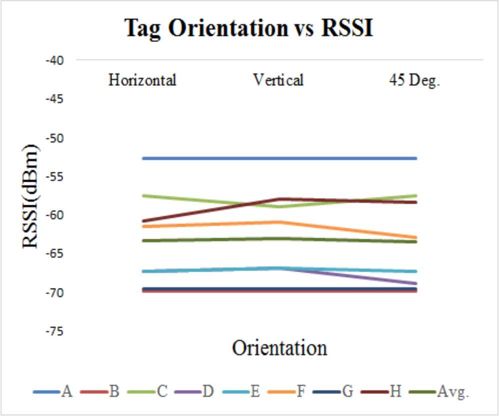


Figure 5.8: Different RFID tags orientations Vs RSSI.

and it was observed that it needs too little reader transmit power compared to passive tags. Using the kitchen foil as a metal material, it was observed that a UHF RFID tag can't operate if a metal is attached over it. By looking to Fig. 5.8, we conclude that most of the tags are insensitive to reading angle.

In Fig. 5.7, the minimum transmit power needed to power a passive tag is shown to be between -1 and 3 dBm (0.0008-0.002 Watts). It also shows that the tag A or the Omni tag is considered the best RFID passive tag as it needs the most little power compared to other RFID passive tags.

In summary, the sensitivity and transmission power of the RFID reader, and the gain of the RFID reader antenna play an important role in determining the maximum read range of a tag. Finally, according to these benchmarks, we can now know which tag to choose for our application. The passive tag that showed maximum read range and needed the most little power to operate and also the tag that competes with the semi passive ones appeared to be the Omni ID Dura 3000 (tag A) and therefore it will be the RFID tag we will use in the proposed smart car parking detection system. To further study this RFID tag and understand how to deploy it, another experiment to identify the best reading angles in the E-Plane is carried out. As shown in Fig. 5.9, tag A has to be interrogated only from the front side from the angles 0 to 45 degress and 315 to 360 degrees. The tag however can be oriented anywhere in the H-Plane, as shown in Fig. 5.8.

5.3.2 RFID Reader-Tag Read Range Measurements

The main aim of this analysis is to identify the maximum distance range that can be covered by the RFID reader antenna-tag pair which will effectively lead to the information that assist in the RFPark system deployment, such as, the number of parking spaces one RFID reader antenna can cover and the RFID reader antenna-tag pair orientation.

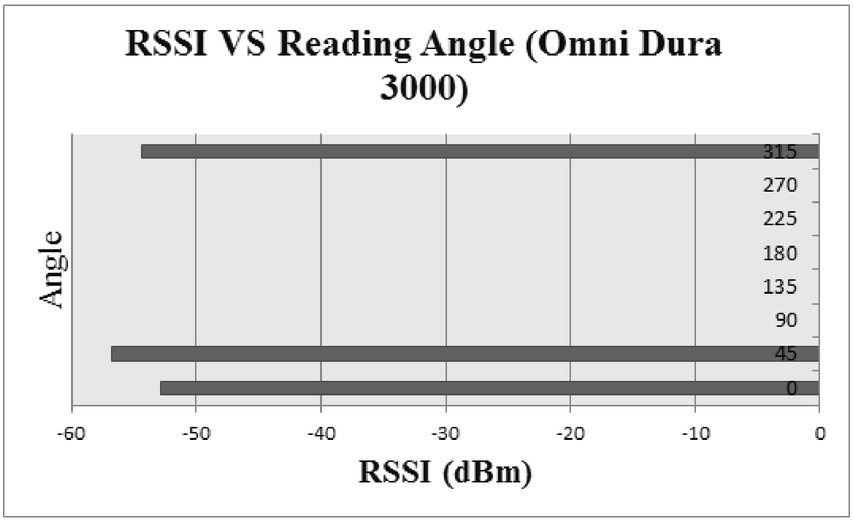


Figure 5.9: RSSI Vs. reading angle for tag A.

5.3.2.1 Theory-based Measurements

The motivation is to identify the maximum read range, A standard test method made by the EPC Global Inc. [77] was used to measure some crucial parameter which the tag min turn on power (See Appendix C for information about the test method). The anechoic chamber was used as the test environment. The first step was measuring the power adjustment factor (this is the total path loss between the reader transmitter and the tag plus the cable loss).

To measure the power adjustment factor, RFID reader antenna acted as the transmitter, it transmitted continuously at known frequency (around 868 MHZ). Then a dipole antenna was used as a reference receiving antenna, and the peak power at its tips was recorded. The factor is equal to the reference antenna gain added to the cable and connector loss subtracted from the total transmitted power.

The second step is to replace the reference antenna with the tag under test, and then the reader will again transmit continuously but with attenuating the power till the tag successful read rate is reduced to 50%. This reader power added to the power adjustment factor calculated earlier will give us the tag minimum turn on power:

$$P_{min,Reader} = -17.931dBm = 16W.$$

Now that we know the minimum power that is needed to reach the antenna of the RFID tag in order for the microchip inside operate, we can estimate the maximum read range in both the forward link (from the reader to the tag) and the reverse link (from the tag to the reader). Using Friis equations below [13] we can calculate those ranges:

$$P_{TX,Tag} = P_{TX,Reader} G_{Reader} G_{Tag} (\frac{\lambda}{4\pi r})^2,$$

$$P_{RX,Reader} = P_{TX,Reader} G^2_{Reader} G^2_{Tag} (\frac{\lambda}{4\pi r})^4,$$

$$R_{Forward} = (\frac{\lambda}{4\pi}) \sqrt{\frac{P_{TX} G_{Reader} G_{TAG}}{P_{min,Tag}}}, \tag{5.1}$$

$$R_{Reverse} = (\frac{\lambda}{4\pi}) \sqrt[4]{\frac{P_{TX,Reader} G^2_{Reader} G^2_{Tag}}{P_{min,Reader}}}. \tag{5.2}$$

Now by substituting all our parameters in Equations (5.1) and (5.2), we get the ranges as following:

$$R_{Forward} = 29m. \tag{5.3}$$

$$R_{Reverse} = 27.5m. \tag{5.4}$$

The maximum theoretical read range is found to be 27.5 meters; in the next section we will try to verify that on practice.

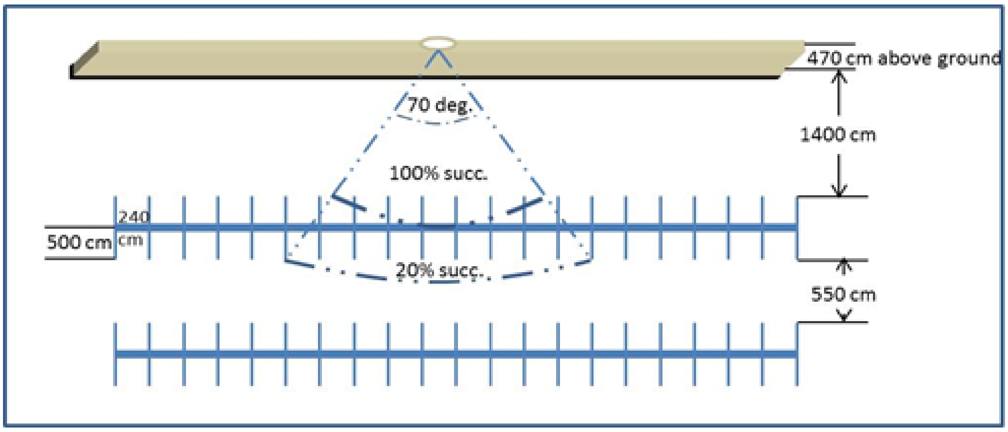


Figure 5.10: Overview of the RFID equipment setup to test the practical read range.

The notations used in the derived equations are as follows: $P_{TX,Tag}$ is the tag transmission power. $P_{TX,Reader}$ is the reader transmission power. G_{Reader} and G_{TAG} are the gains (with respect to an isotropic radiator) of antennas of the reader and the tag respectively. r is the distance between the antennas of the reader and the tag. λ is the wavelength. $P_{min,Reader}$ is the reader sensitivity. $P_{min,Tag}$ is the tag minimum turn on power. Finally $R_{Forward}$ and $R_{Reverse}$ are the reading range in the forward (from the reader antenna to the tag) and reverse (from the tag to the reader antenna) links respectively.

5.3.2.2 Practice-based Measurements

Now that we know the theoretical read range, the motivation of this experiment is to identify the maximum practical read range of the RFID system coverage of one antenna, the best orientation and position of tag related to ground, and the effect of cars on the RFID system.

As shown in Fig. 5.10, the RFID reader was connected to a circular mono-static antenna with 70 degree beam width and powered by the Impinj Speedway Reader with source power at antenna port of 30 dBm. On the other side, Omni ID Dura 3000 RFID tags were attached to the ground more than 15 meters away from the reader side. The reader side was about 5 meters and the antenna was positioned to be inclined by 20 degrees towards the ground.

To identify the maximum range, the tag was kept in the 70 degrees coverage region of the antenna and positioned to it. Then the tag was moved away from the antenna in all directions inside the 70 degree cone and maximum range is recorded when the reader cannot detect the tag anymore. Identifying best orientation and position of the tag related to the ground was done by firstly attaching the tag to the ground few little meters away from the antenna and RSSI is recorded then the same procedure further meters away from the antenna. Secondly the tag is separated 1-2 centimeters above the ground and oriented to the antenna and range is recorded. Last and to examine the effect of neighbor cars to a tag, the tag was positioned 2 centimeters above the ground and positioned to the antenna and located in the middle between 2 parked cars.

The maximum range achieved in this experiment is 25 meters: 7 meters had a 100% success read with tags directly attached to the ground, 19 meters had a 100% success read with tags 1.5 cm above the ground and positioned to the antenna, and 25 meters with 20% success read with tags 2 cm above the ground and oriented to the antenna. The tag can be read 16 meter away from the antenna and when it is located in the middle between 2 cars (separated by 50 cm) and 4 cm above the ground and oriented to the antenna.

It is concluded from the experiment that: 1) the ground has direct effect on the RFID system and the tags can't be attached directly to the asphalt, there must be a separation of at least 1 cm. This leads also to the conclusion that other materials attached beneath the tag could improve the read range. 2) The tag must be oriented to the antenna when it is 14 meters away and more from the antenna in this experiment. 3) Maximum practical read range is 2.5 meters less than the theoretical range which proves the accuracy of our calculations. The range could be improved if the mono-static reader system is replaced with bi-static reader system where there will be a

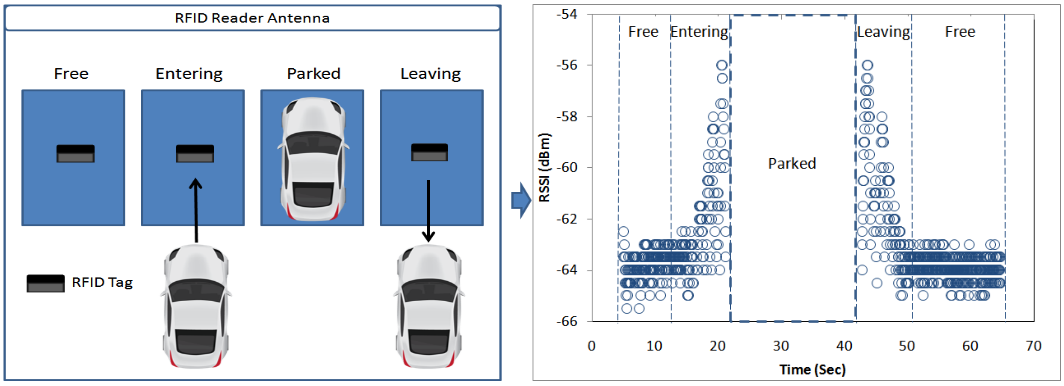


Figure 5.11: RSSI signature for a vehicle parking operation. The signal is completely absorbed by the vehicle metals when the vehicle is completely covering the RFID tag.

separate transmit and receive antennas. 4) A Maximum of 25 meters read range had been achieved leading to a maximum of 15 car parking spots could be monitored using this setup; more spots could be covered using another setup.

5.3.3 Performance Analysis

In this section, the new RFID detection system is analysed in a typical outdoor car parking environment, as shown in Fig. 5.14. Three different operations were investigated. The primary operation is a vehicle parking over a RFID Tag. The second operation analyses the effect of interrogating a RFID tag deployed in a vacant parking space when another vehicles are parked in the neighbor parking spaces. The third operation explores the potential limitations of the RFID system in a real world parking environment where people and cars are randomly moving around.

In all the following experiments, the RFID reader antenna was positioned inside a foam at about 20 meters away from the RFID tags and was placed 5 meters above the ground level. In addition, the transmitting power was set to the maximum of 30 dBm according to the FCC regulations.

5.3.3.1 Parking Detection

In Fig. 5.11, the RSSI signature of a vehicle parking process is shown. A typical parking period composes of three stages: entering, parking-stop and leaving. At first, the parking spot is vacant and the RSSI is between -65 dBm and -63 dBm. When a vehicle then enters the parking space- just before covering the tag, the RSSI increases by 7 dBm. This behaviour is partially dependent of the type of the RFID tag. In fact, some tags are optimised to work better on metals and others off metals. The Omni 3000 tag contains a patented plasmonic structure that is optimised so that the interference by metals or water contributes to the RF field in a constructive way.

The next stage is parking-stop where a vehicle completely covers the RFID tag. It is observed here that the RF signal is never received back to the reader from the tag. As expected, the UHF signal that has typically 10-100 cm wavelength, is blocked by the vehicle. At this point, the detection system will decide that a car has parked. Finally, it is seen that the RSSI returns back to its previous values when the car is leaving and the spot is vacant again. The detection system will then decide that this parking spot is vacant.

5.3.3.2 Object State Analysis I

Now that the detection approach is working in principle, it is time to analyse the basic different scenarios for the parking environment to improve the detection accuracy. Firstly, it is vital to ensure that the RFID tag deployed in a vacant parking spot can be interrogated when surrounded by vehicles in neighbor parking spots. As depicted in Fig. 5.12, four object states were analysed: 1) vacant with no neighbor cars, 2) vacant with a car in one side, 3) vacant with cars in both sides, and 4) vacant with a car in back side. The results show that when the tag in a vacant parking spot is surrounded by vehicles, the tag is still interrogated and read. Moreover, the RSSI

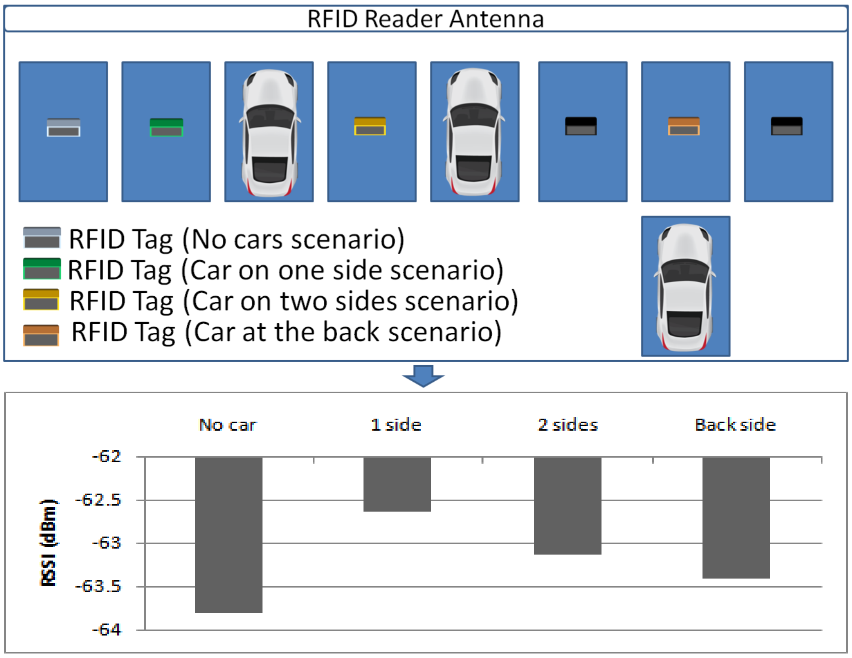


Figure 5.12: Average RSSI for 4 different object states. 1) Vacant with no surrounding cars. 2) Vacant with a car in one side. 3) Vacant with cars in both sides. 4) Vacant with a car in the back side.

slightly increases on average in the three states as compared to the vacant and no cars state.

5.3.3.3 Object State Analysis II

In any parking environment, it is natural that people and vehicles (objects) are going to be moving around the parking spots. As a result, the RF links between the RFID antennas and tags might get blocked by the passing objects. In Fig. 5.13, this effect is illustrated at position 2 where vehicles or people are located exactly between the RFID reader antenna and the tag. The period at which the signal is blocked is relevant to the height of the object and the proximity between the object and the RFID tag in this scenario. When the object is not close to the tag, the period is much smaller, because the RFID reader antenna is placed above the ground by about 5 meters. Finally, it was observed that the RSSI increases by the average of 2 dBm

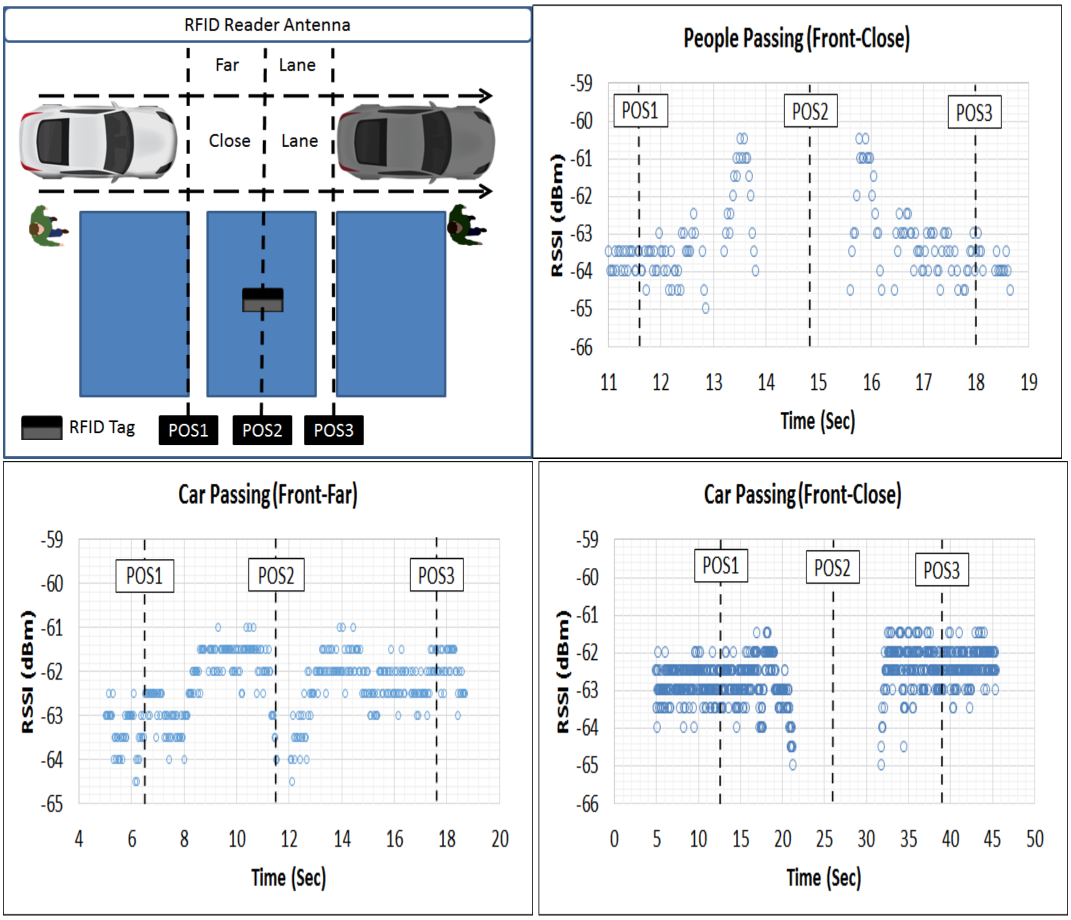


Figure 5.13: RSSI signatures during objects movements.

when the object is between the positions 1 to 2 and 2 to 3. When the object is a person, this increase is about 3 dBm and when the object is a car, it is about 1 dBm.

5.3.3.4 Detection Accuracy

Based on the previous analysis, the detection system may trigger false parking detections when a passing object alters the line of sight between the RFID antennas and the tags. Hence, a detection window technique shall be adopted to mitigate this. For instance, instead of deciding the occupancy state of parking spaces in real time with no delay, the decision will be made every predefined interval, named as observation time t. This will allow the RFID reader to interrogate the tags multiple times before generating the tags report. Thus, if a vehicle or a person blocked the

(a) RFID reader and antenna connected and positioned towards an outdoor parking lot.

(b) Omni Dura 3000 passive tag on the asphalt and oriented to the reader antenna.

Figure 5.14: Performance analysis setup in an outdoor parking in the University of Liverpool.

Table 5.1: Observation time vs. accuracy

t (Sec)	0.5	1	3	5	10	15
VDR	24%	49%	81%	91%	98%	100%
ODR	100%	100%	100%	100%	100%	100%

t: Observation time. VDR: 'Vacant' detection rate. ODR: 'Occupied' detection rate.

radio link for a few seconds and then left, given that the parking spot was vacant, the RFID reader will still report the tag EPC and the spot will be detected as vacant.

In order to determine the shortest observation time t for the best detection accuracy, 6 tags were deployed in the proximity of the RFID reader antenna as shown in Fig. 5.16. The RFID reader was then configured to read the tags and generate the tags report every different observation times. In addition, this experiment was performed in the presence of passing cars and people. The detection accuracy of the RFID detection system is measured on the basis of the 'vacant detection rate' and the 'occupied detection rate'. The detection rate in general is the ratio of true to false detections of the state of the parking spaces- either vacant or occupied.

As shown in Table 5.1, the vacant detection rate is significantly affected by the observation time. At t=0.5 seconds, more than 70% of the vacant detections are false. This is primarily because an object will spend at least a few seconds in the passing process. The vacant detection rate is then observed to increase by about 20% after every second increment to the observation time. Finally, when t is set to 15 seconds, the vacant detection rate is 100%. On the other hand, the occupied detection rate is found to be 100% for any given t as expected. This concludes that a value larger than 15 seconds for the observation time will result in a robust detection system.

5.4 System Implementation

As previously discussed, the RFID reader is set to interrogate the RFID tags continuously and send the tags report to the central server every predefined observation time

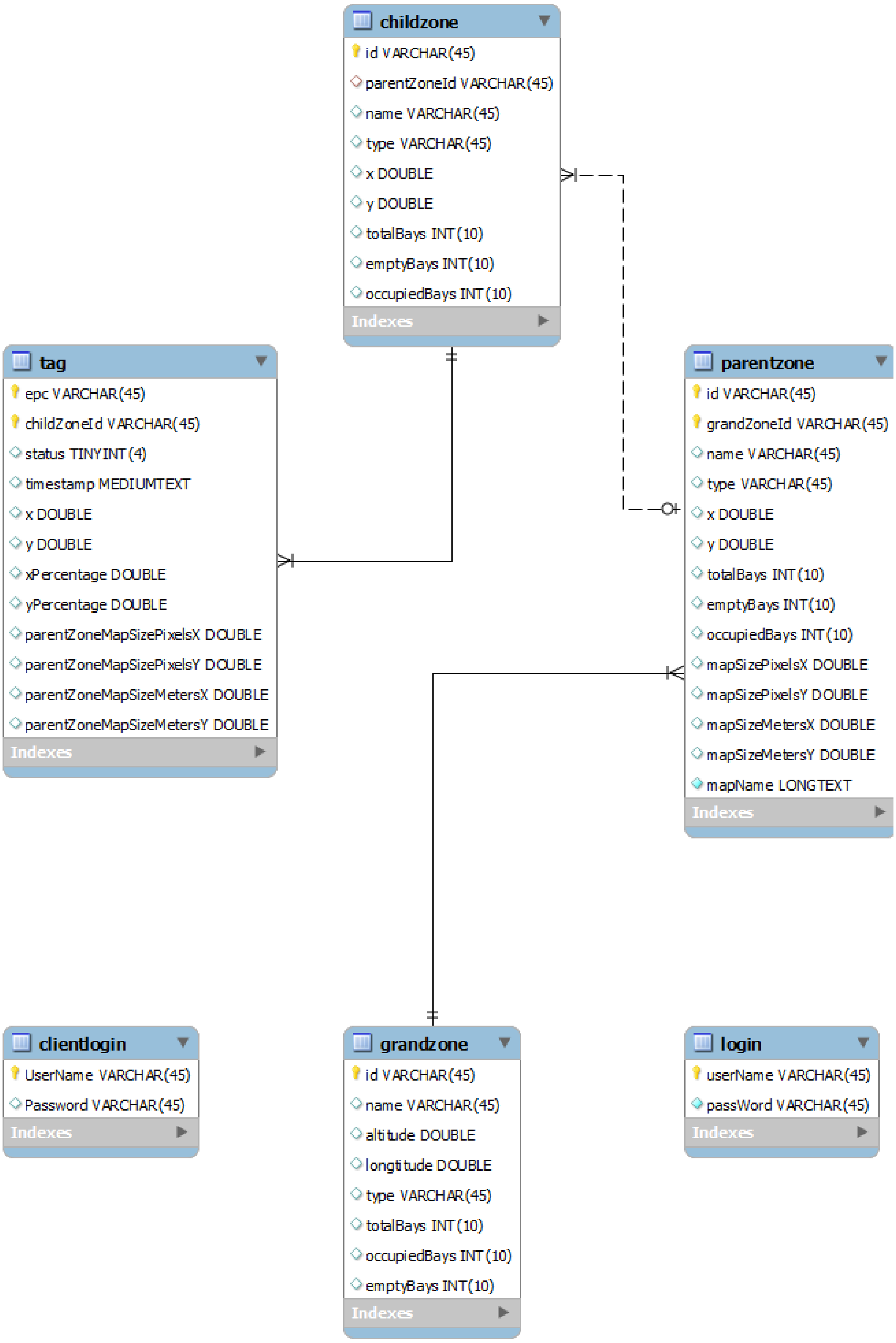


Figure 5.15: RFPark central database model.

t. The report contains the read tags IDs, the RSSI and the tag-first-seen timestamp. It is important to mention that the report will contain many duplicate entries, as the RFID tags had been read multiple times during the period t. The report is filtered at the central server and then compared with the pre-known tags IDs for this parking area (recall that the planner software is firstly used to generate the digital map and store its information in the central database). The comparison process is performed by looping over each tag ID in the digital map and checking whether or not the tag ID of the filtered report matches it. If the IDs are matched, then the central database will be updated and the corresponding parking space will be recorded as vacant in the 'current parking states' table. Else, the parking space will be recorded as occupied.

The central database - whose model is shown in Fig. 5.15 - also stores the entry and exit times of the parked vehicles in the 'History' table. The parking timing information is obtained using the following process: 1) if the new current parking

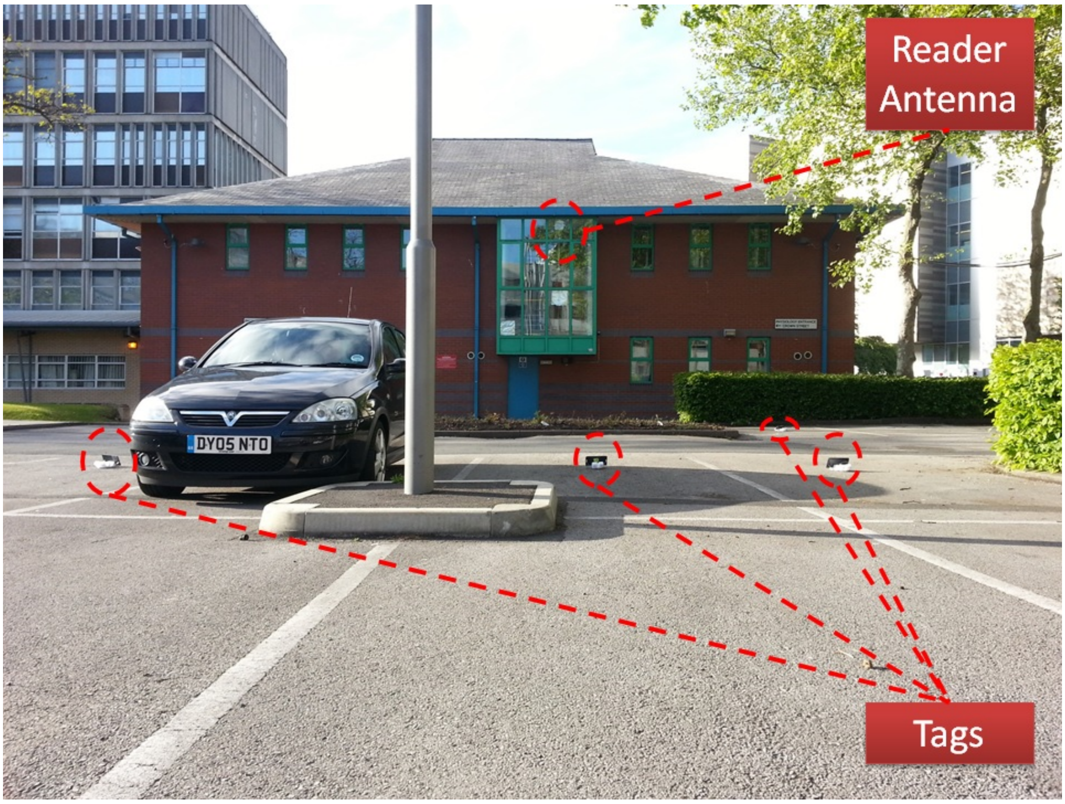


Figure 5.16: Pilot study in an outdoor parking in the University of Liverpool.

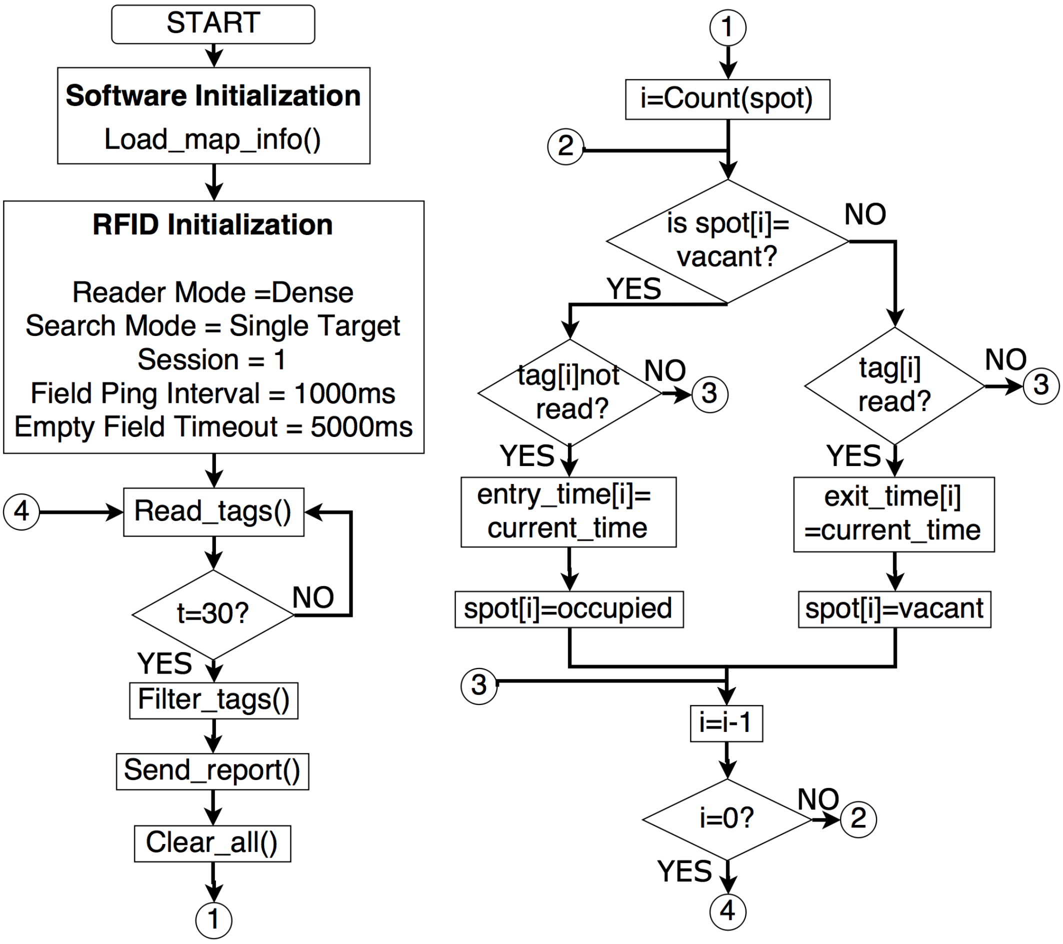


Figure 5.17: The parking detection algorithm. Spot[..] is the array of parking spots statuses that are located in the central database. Whereas tag[..] is the array of reported RFID tags statuses. Entry_time[..] and exit_time[..] are both arrays of the entry and exit times of parked vehicles.

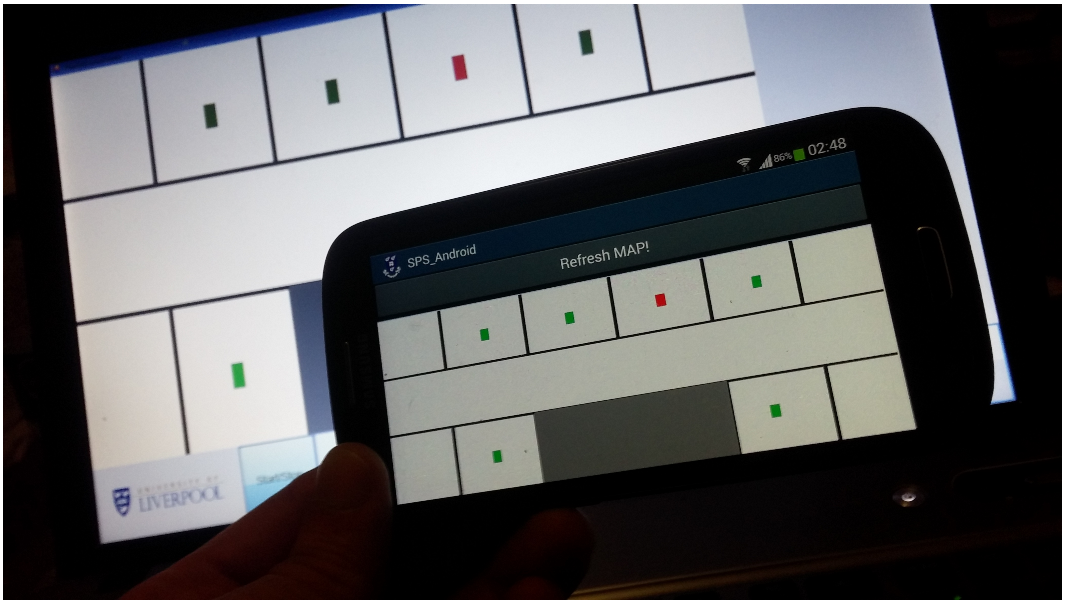


Figure 5.18: RFPark Windows and Android applications.

state is ‘occupied’ and the previous parking state was ‘vacant’, then a new entry will be put in the history table stating the parking spot ID and the entry time. 2) if the new state is ‘vacant’ and the previous state is ‘occupied’, then the entry that was created earlier will be updated with the exit time. 3) if the new state and the previous state are the same, then no changes to the table will occur. The complete process is further illustrated in Fig. 5.17.

The new RFID detection system, as described in this chapter, has been deployed in an outdoor parking lot at the University of Liverpool (see Fig. 5.16). For the purpose of research, 6 parking spaces were monitored for 7 working days. We have also installed cameras to record all the events of motion around the parking spaces, such that the decisions of the RFID system is verified with the camera footage. A smart-phone and Windows application are also built (see Fig. 5.18), through which the users can view the real time parking information published by the central server. The accuracy of the decisions made by the new RFID detection system is 100% correct using the observation time of 30 seconds only. In addition, the system had performed with the same efficiency throughout the different weather conditions.

5.5 System Realisation Challenges

The main challenges belonging to the realisation of our proposed RFPark system can be summarised as follows.

5.5.1 Interference

In a typical car park with RFPark system installed, there will be hundreds or even thousands of parking spaces which will require the deployment of the similar quantity of RFID tags and numerous RFID readers. There is a high probability that a portion of the readers will enter the interrogation region of other readers around them. In this scenario, a dense RFID system is formed and many challenges are introduced. First, the RFID readers don’t know about other readers’ existence since they lack the communications between each others. This may lead to signal interference if the readers transmit their waves at the same frequency. This type of interference is called reader-reader interference. Second, passive tags, which lack frequency tuning circuitry, can’t differentiate between readers and therefore will cause interference if they got interrogated by the same readers. This type of interference is called reader-tag interference.

In order to overcome the interference problems, certain regulations, standards and collision algorithms have to be taken into account while designing the RFID system [78]. Today, there are 2 main parties that regulates the use of radio systems including RFID: The first is the European Telecommunications Standards Institute (ETSI) and it is a standardization organization in the telecommunications industry in Europe. The second is the Federal Communications Commissions (FCC) and it has similar duties like ETSI but for the United States of America (USA) instead. In ETSI regulations, RFID readers have to utilise the Listen-Before-Talk (LBT) multiple access technique. With LBT, a reader senses the carriers of channels before transmitting. Then the reader is only allowed to transmit once the carrier channel is idle. In FCC regulations, the given spectrum is divided into several frequency bands then the RFID readers use Frequency Hopping Spread Spectrum to hop between those frequencies [79].

Although these regulations significantly reduce the interference problems, they don't overcome the reader-tag interference. In response to this, EPCglobal developed global standard protocols for RFID. For instance, EPC Class 1 Generation 2 (Gen2) UHF protocol [80] states that frequency hopping is to be used for efficient frequency utilisation. However this time the frequency hopping is different from that of FCC. With Gen2, reader transmissions operate in even-numbered channels and tag backscatters are found on odd-numbered channels. This way the reader and tag transmissions are done over different frequency channels.

Regulations and standards are essential to be applied when designing RFID systems to ensure devices compatibility and lower radio interferences. Due to rapid RFID development, several reader anti-collision algorithms have been developed to further reduce reader-reader and reader-tag interferences [78]. The algorithms are mainly based on scheduling or on the principle of a notification mechanism of broadcasting control packets. Scheduling-based algorithms include Time Division Multiple Access (TDMA) anti collision algorithms and their objective is to allocate resources such as frequencies and time among the readers so that the simultaneous transmissions are avoided. Control Mechanism-based approach let the readers transmit notification control packets before transmitting. When the interfering readers receive this notification, they interrupt their communications and wait for the next cycle.

Based on these, the RFID equipment must be carefully chosen, such that standards and regulations are followed and that anti-collision algorithms for RFID dense environment are operating.

5.5.2 Security

RFID is still an emerging technology, therefore the development of standards and protocols to protect and secure the RFID chips is still being explored and strengthened. Fortunately, the security threats that may affect the realisation of RFPark are not as much as of that in other RFID applications. That is because in RFPark there are no sensitive data being communicated other than the EPCs of the RFID tags. However, there are still some important security threats that have to be addressed:

- **Jamming:**

  This involves the use of a device that actively transmits radio signals in the frequencies of that of RFPark at high powers. This effectively will alter the operation of the RFID readers in the device's coverage zone. Jamming in the car park will cause the RFID readers to not be able to interrogate the RFID tags and therefore the parking spaces will always be detected as occupied.

  Frequency jamming is illegal and fortunately there are ways to detect it [81]. Once jamming is detected, the parking manager should inform the relevant authority. Jamming can also not cause a system failure if the RFID readers are performing frequency hopping. Since it is very hard for the attacker to perform active jamming over a spectrum of frequencies.

- **Zapping:**

  RFID zapping is attacking the RF front-end of RFID tags by sending a short high-power pulse towards the antenna of the tag under attack from a device called zapper. When the pulse flows through the tag's antenna, the power harvesting circuit of the tag is overwhelmed, killing the tag.

  This attack is less dangerous as compared to jamming. Because in jamming, the operation of RFID readers is altered, making the detection of several tags impossible. Where as in zapping, only one RFID tag operation is stopped.

That said, it is still an important security threat. Unfortunately, the only way to avoid zapping is to make the RFID tags unreachable completely, which is not practical. The easiest way to overcome this threat is to monitor the parking lot with CCTV cameras and track suspicious actions in the car park. The damaged tags can be easily identified at the car park non-operation time, where all the parking spaces are vacant. At this time, parking spaces with damaged tags will be shown as occupied.

- **Eavesdropping and Spoofing:**

  This occurs when an attacker intercepts the information exchanged between the RFID reader and the tags using a compliant reader for the correct tag family and frequency then reuse it to simulate the RFID tags [82]. This is the most common security threat that can face the RFPark system. One can interrogate the RFID tag at a parking space, read its EPC and then write it to another RFID tag installed at the top of his/her vehicle. This will effectively allow a driver to park their vehicle without being detected.

  The threat of spoofing can be eliminated using the Transponder Identification (TID) of the tag. TID is a read-only identification number that is programmed into the tag by the tag's manufacturer. As the TID is a read only number, the attacker now, even if he/she has cloned the EPC and knows the TID of the tag under attack, he/she will not be able to write that TID to his/her cloned tag. Therefore to protect RFPark from spoofing attacks, RFID readers have to report the EPCs and TIDs of the tags and compare them with the original EPCs and TIDs stored in the RFPark database. If a mismatch in TIDs is found, an alert to the parking manager can be made to inform about a spoofing attack at the tag under attack exact position.

  Another similar attack to spoofing is to rewrite the EPC of the tag under attack. Fortunately, this is very simple to overcome by using read and write access passwords. It is important to note that feature like access passwords and TID may only be available in EPC Gen2 tags.

5.5.3 Other Challenges

So far, interference and security issues and solutions to them have been addressed. However, there are still some challenges that may affect the realisation of this system. A major concern by the city councils - in the case of public parking management - or the private parking owners, is the cost of implementing such a system. In this piece of work, expensive RFID reader equipment was used and approaches to minimise the number of RFID readers and antennas in a typical car park were not explored. Thus, the implementation of RFPark may be currently very expensive as compared to other parking detection approaches. However, there are 2 main approaches that are guaranteed to dramatically reduce the implementation cost.

First, there is no need to use expensive RFID readers, such as the one used in this dissertation - the Impinj Speedway Revolution readers. These expensive RFID equipment provide several features that are not utilised by our application. Alternatively, it is possible to design one’s own RFID reader equipment that contains the minimum electronic components that effectively allow RFPark to operate. Second, further research should be done to increase the reading of each RFID reader antenna. This will increase the number of parking spaces that can be covered by a single RFID reader antenna, and therefore lowering the number of RFID equipment required, thus lowering the implementation cost.

Another challenge is to lower the risk and cost of system failure. There are four main components of our RFID system: reader, reader antennas, tags and central server. For the RFID reader and antennas, the risk of their failure can be reduced by decreasing the operational time of the RFID reader throughout the day. This can be achieved by running the RFID reader on a timer-based method, e.g., from

9 AM to 5 PM. In addition, the interrogation of the tags also be performed every pre-defined interval, e.g., every few seconds. By using this strategy, the lifetime of the RFID reader and reader antenna shall be very much increased. However, there is still a risk that the RFID reader fails to operate at some time, and therefore the car park monitoring operation will be affected. One way to tackle this problem is to constantly monitor the operation of the RFID readers by programming them to send a network packet to the central server stating their operation status. Once that network packet is not received in time, the central server can alert the parking manager to investigate the RFID reader fault.

The central server is a core part of RFPark's operation and its failure means a complete shutdown to RFPark's services. There are methods and strategies to protect the central server against failures, but it is out of the scope of this dissertation. Finally, the RFID tag has the lowest risk of failure, since it is a passive component and thus can have a lifetime of more than 20 years.

5.6 Conclusions

There are many technologies that can be used as the core sensor technology for 'Smart Car Parking' systems. However, each of them has its own limitations, such as the sensitivity to weather conditions, the complex installation and the frequent maintenance. In this chapter, we demonstrated for the first time that UHF passive RFID tags deployed on the asphalt can be used to detect the occupancy state of parking spaces. This is achieved by fixed RFID reader antennas that interrogate the RFID tags placed on the asphalt for predefined time interval and update a base station that publishes the parking information online to client applications. The read tags imply 'vacant' parking spaces and the rest imply 'occupied' parking spaces.

Extensive measurements had been performed to study the performance of different RFID tags both indoors and outdoors. These measurements allowed the optimal choice of the RFID tag to suite the system and gave information and guidelines for the tags deployment in the parking environment. Following that, the chosen RFID equipment was further tested to calculate the maximum read range. This effectively assists the system planner for deciding the number of RFID tags one RFID reader antenna will cover.

In addition, the RFID detection system was analysed and implemented in a real world outdoor parking environment and further experiments were carried out, such as, the parking detection and the effect of passing people and cars over the RFPark system accuracy. Based on those experiments, an algorithm was developed to ensure a parking detection accuracy of 100%.

Nevertheless, there are many challenges belonging to the realisation of this system and they have to be considered while implementing RFPark. First, reader-reader and reader tag-interferences can occur when there are multiple RFID equipment are in close proximity to each other. To overcome this, RFID regulations and standards have to be applied. In addition, anti-collision algorithms have to be implemented in the RFID reader software. Second, this system is threatened by many security attacks, such as, jamming, zipping and spoofing. In order to minimise the risk of these attacks, the correct RFID equipment have to be used. For example, the RFID reader has to be able to do frequency hopping and the RFID tags should be compliant with EPC GEN2, such that they can be protected by access passwords. Third, the cost of the system implementation is currently expensive. However, it can be significantly reduced by developing cheaper RFID reader equipment and designing a RFID system that allows the coverage of larger number of RFID tags.

Chapter 6

Conclusions and Future Directions

6.1 Conclusions

Traffic congestion leads to some critical problems and challenges in most urban areas. It reduces the efficiency of transportation resources and increases travel time, pollution and fuel consumption. To alleviate those problems, it is direly needed to build new facilities and smart information technologies for transportation systems. In this dissertation, we proposed three smart car parking systems in the domain of intelligent transportation systems who are designed to solve different problems in this area. We sum their topics up and emphasise our contributions as follows.

The state-of-the-art smart car parking systems, such as PGI systems, PRS systems, etc. were reviewed and it was observed that there are several shortcomings of these guidance-based systems. Chapter 3 proposes a novel smart parking system - named iParker - which is based on MILP model that yields optimal solution for dynamically and statically allocating parking lots to drivers - providing flexible reservation options. The new concepts introduced in this chapter are the combination of real-time reservations with share-time reservations, dynamically performing system decisions (reservation time constraints and pricing) according to information on real-time resource utilisation, and offering the drivers the choice of choosing multiple destinations and reservation type.

As opposed to the current smart parking systems, iParker includes new components, such as Parking Manager, Pricing Engine and Smart Allocation Center. The Parking Manager is an interface that allows parking authorities to view and alter the settings of the Pricing Engine. The Pricing Engine is responsible for dynamically fixing the right parking and reservations fees for parking lots. The Smart Allocation Center is the central module to make optimal allocations decisions. Chapter 3 also proposes new pricing policies for both static and dynamic reservations that maximises the profit from parking.

The main challenge of implementing iParker - especially for the outdoor parking - is the reservation guarantee, i.e. preventing parking spaces from being occupied by other drivers who are not reserving it. A light system scheme along with a smart parking law enforcement collaboration-based method have been proposed to solve this problem. First, colours are used to indicate the status of parking spaces. For instance, RED to indicate a parking space is reserved. Second, in the event of illegal parking - the driver with reservation didn't confirm their occupation of parking spaces at the time the parking space was occupied - the enforcement officers will be notified and informed with the parking space identification number.

In addition, scalability issues were discussed and several ways to reduce the problem scale were proposed. Extensive simulation results indicate that iParker significantly cuts the total effective cost for all drivers, maximises the total utilisation and increases the total revenue for parking management as compared to the non-guided parking system. In addition, a dynamic pricing scheme has been proposed and by integrating it to iParker's model, it is found by simulations that it balances the utilisation across all the parking resources and thus assisting in further reducing the overall traffic congestion caused by parking. The iParker system allows drivers to reserve a random space in a parking lot. This does significantly reduce the travel time as compared to guidance-based systems. However, the travel time by car towards the parking space in the car park, and the commuting time by foot inside the destinations can still be reduced if the driver is able to reserve a specific parking space instead of a random one. This has been achieved in Chapter 4 where the system, called INDO, has been proposed. INDO is a novel smart indoor commuting and car parking system which is based on a new MILP model that yields optimal solution for allocating parking spaces to drivers - providing the least cost in terms of the total commuting time - based on the knowledge of the car park and the destination building layouts.

The new concept introduced in chapter 4 is the combination of resource allocation and the indoor navigation and guidance. As opposed to iParker, INDO includes two new components, the Planner Software and the RFID/NFC systems. The Planner Software is first used by the parking manager to convert the layouts of the car park and buildings into digital maps. The digital maps contain information about the entrance/exits of the car park and buildings. In addition, they contain information about the points of interests (POIs) inside buildings and all the possible routes to and from the gates. Furthermore, they contain a cost table which provides data about the driving and walking costs in the car park and buildings that are to be used by the Allocation System for allocation decisions. The RFID/NFC systems include RFID/NFC enabled devices that are carried by the drivers, and RFID/NFC tags that are deployed in the car park and buildings to aid the navigation and guidance processes.

An example application of INDO could be in a giant shopping mall where it is served by thousands of parking spaces that are partitioned as multiple small car parks. Drivers will be able to use the INDO app before or at arriving in the vicinity of the shopping mall to search for and choose a specific shop inside that mall. On the other end, the Allocation System will immediately reserve the best parking space for the drivers and notify them with the ideal gates they should use. Furthermore, the drivers will be able to take the shortest route to their destination using the app's navigation, saving them a substantial commuting time in the building. Using the app's navigation, the drivers will also be able to return to their cars, eliminating the chances of forgetting where the car is parked.

The parking and commuting processes for INDO, guided and non-guided systems have been modelled and evaluated. Simulation results indicate a significant reduction in the total commuting time as compared to the non-guided systems. Furthermore, the resource allocation component in INDO has shown a 10% reduction in commuting time as compared to the guided systems - the indoor navigation and guidance systems. On the other hand, INDO maximises the service ratio in dense traffic, such that the parking areas can serve more arriving users as compared to the guided and non-guided systems. Moreover, a software package was developed and the system implementation was discussed.

The third smart parking system, entitled RFPark, has been proposed in Chapter 5. RFPark is a novel parking spot occupancy detection system that overcomes the majority of the sensor limitations found in state-of-art PGI systems, such as the sensitivity to weather conditions, the complex installation and the frequent maintenance. In this chapter, we demonstrated for the first time that UHF passive RFID tags deployed on the asphalt can be used to detect the occupancy state of parking spaces. Fixed RFID reader antennas interrogate the tags for predefined time intervals and update a base station that publishes the parking information online to client applications. The read tags imply 'vacant' parking spaces and the rest imply 'occupied' parking spaces.

Intensive measurements to study the performance of different passive RFID tags, both indoors and outdoors, have been performed. Based on these measurements, the most suitable RFID equipment have been identified. The theoretical and practical read ranges have also been calculated to identify the number of RFID tags that one RFID reader antenna will cover. Furthermore, a smart phone application, a Planner Software, a Central Server and a Windows application have been developed.

The RFID detection system was analysed and implemented to show a pilot study in a real world outdoor parking environment at the University of Liverpool and has proved a very high detection accuracy. The challenges belonging to the realisation of RFPark and solutions to them have been addressed in Chapter 5. These include interference and security issues. Nevertheless, if the right RFID equipment is deployed and correctly configured, the realisation of challenges will be alleviated.

6.2 Future Directions

The following is a list of possible avenues for the continuation of this work:

- **iParker**:
  - Re-evaluate the system using real-time data and greater number of resources and destinations.
  - A scalability analysis is to be performed to examine the efficiency of the proposed scalability techniques.
  - Simulate different parking arrival scenarios in real life.
  - Utilise K Dimensional Tree method for static reservations (KDTree), which will significantly reduce the computing power for static reservations.
  - Formulate algorithms for future prediction of multiple trends, e.g., predicting the duration of stay time and price and walking constraints of future drivers. This will lead to an increased parking revenue and utilisation.
  - Research and develop novel methods for parking reservation guarantee for the uncontrolled areas.
- **INDO**:

  - Further develop the system by implementing revenue making functions, such as advertisement and marketing campaigns through the INDO application.
  - Enhance the positioning component of the system by integrating the data from the motion sensors found in smart phones.
  - Research and develop novel methods for parking reservation guarantee in uncontrolled areas.

- **RFPark**:
  - Design and build a special passive RFID tag and reader antenna that yield a greater sensing coverage for the parking areas.
  - Research and develop novel methods to interrogate RFID tags with lower number of RFID reader antennas.
  - Formulate machine learning algorithms that can be used with the low level RFID reader data to improve the RFID detection system in complex parking environments.

Finally, iParker, INDO and RFPark can all be combined to form one smart car parking system as shown in Fig. 6.1. iParker can allocate drivers a random parking space in a whole parking lot - either on-street or off-street - whereas, INDO can allocate specific parking spaces in that whole parking lot. In other words, iParker is a countrywide allocation and reservation system, whereas INDO is a smaller scale (e.g., shopping mall parking) allocation and reservation system. When INDO is integrated with iParker, the drivers' cost will significantly decrease. On the other side, RFPark can act as the parking detection sensor sub-system for iParker and INDO to update the allocation centers with occupancy states.

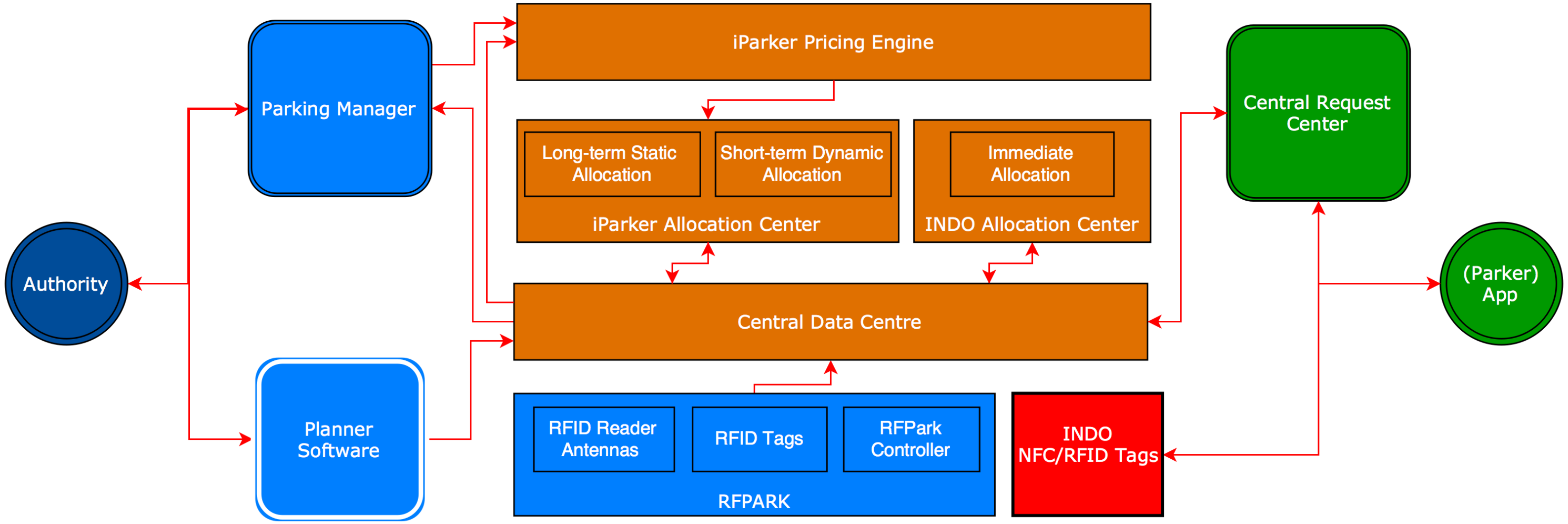


Figure 6.1: System architecture combining iParker, INDO and RFPark.

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Appendix A

Background Material

In our proposed systems - iParker, RFPark and INDO, we have utilised advanced mathematical modeling methods, algorithms and identification technologies. In this section, we describe the Mixed Integer Linear Programming (MILP) utilised in iParker and INDO, Passive Radio Frequency Identification (RFID) utilised in RFPark, and Dijkstra's algorithm utilised in INDO.

A.1 Mixed Integer Linear Programming (MILP)

A mixed integer linear program is an important class of constraint optimisation problem. MILP has several applications in the industrial production, scheduling and telecommunications [83, 84]. It compromises of discrete and continuous variables, linear constraints on those variables, and an objective function that has to be minimised or maximised [85]. MILP problems are NP-complete, meaning that the computational time finding optimal solution increases exponentially with the size of the problem in the worst case [86]. Current commercial MILP solvers/optimisers use intelligent search methods to overcome the computational time problem [87].

The most common search method is the Branch and Bound technique [88]. It is used in Microsoft Excel, Premium Solver, XPRESS Solver, Gurobi Solver, and

IBM ILOG CPLEX [87]. The idea of branching is to divide the large problem into multiple small sub problems. Whereas bounding is to estimate the quality of the solution that can be obtained from each sub problem. This is done by using linear programming relaxation: drop the requirement that all variables are to be integers, and keep the objective function and constraints to obtain a linear program. If a LP problem has an integer optimal solution, the solution would be compared with the best solution so far – called incumbent –, and the searches with higher lower bound are terminated.

Branch-and-cut is another method that is commonly used [89]. For branch and cut, the LP is solved without the integer constraints and the lower bound is again produced by the LP relaxation of the integer program. At the point when an optimal solution is acquired, and a non integer value for a variable that should be an integer is in this solution, a cutting plane algorithm might be utilised to discover further linear constraints which are fulfilled by all feasible integer points however violated by the current fractional solution. Cutting planes are iteratively gotten until either an integral solution is obtained or it becomes very expensive or impossible to obtain another cutting plane. A conventional branch operation is carried out and cutting planes search continues on the sub-problems in the later case.

A.2 Radio Frequency Identification (RFID)

RFID is an emerging technology that complements the bar-code technology developed in the 1960s, while the applicability of data capture and computing products are extended [91]. It uses RF waves to interrogate or read objects known as transponders or tags. Each tag contains memory banks which at least store one unique ID, called Electronic Product Code (EPC) that uniquely identifies this tag. Additional memory could be available to store some user and product information. A typical system consists of RFID reader, a cable attached to zn antenna and a tag [92].

As shown in Fig. A.1, there are three types of RFID tags [93]: Active tag which uses internal battery to boost the power of the signal for very long read range (few hundred meters to kilometers) and it contains its own transmitter. Passive tag which uses no batteries and have a very long lifetime but have limited read range (few meters). Last the semi passive tags which use a battery to boost the data to the reader, however it only gets activated when the reader is reading the tag, therefore battery life is much longer than the active tags.

Passive and semi passive tags don't have a radio transmitter like active tags do. However, they take advantage of using the modulation of the reflected power from the tag antenna, known as 'Backscattering' [94].

RFID systems are introduced in different versions that work at different frequencies. The choice of the frequency at which the RFID system works at is dependent

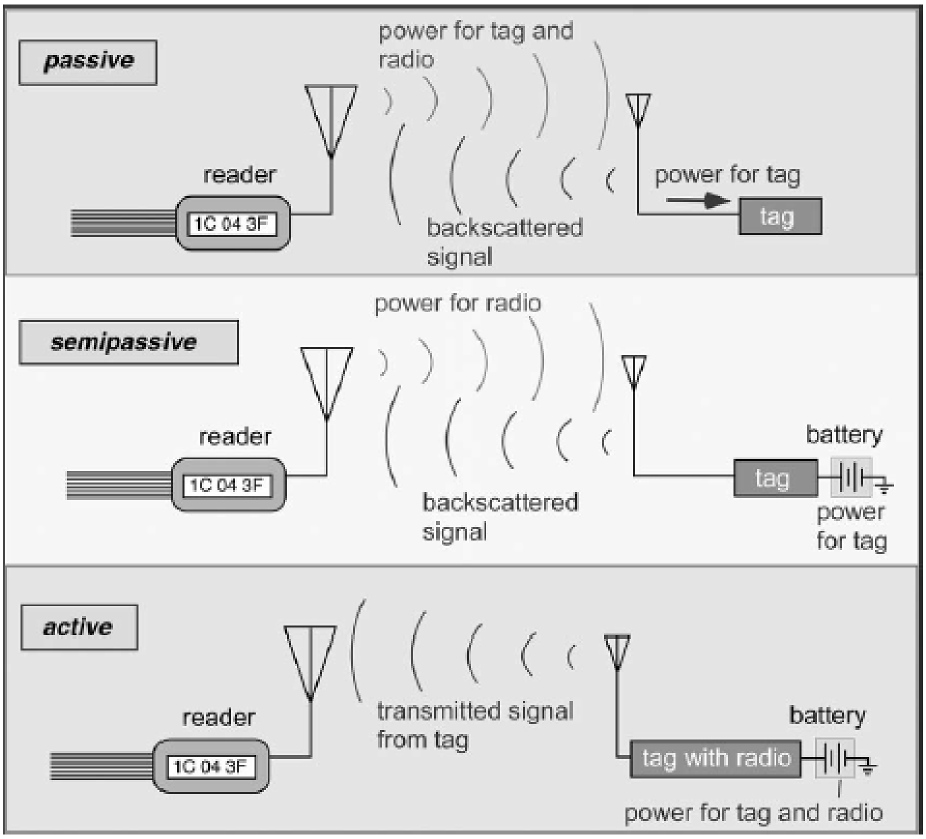


Figure A.1: Difference between active, semi-Passive and passive RFID. [90]

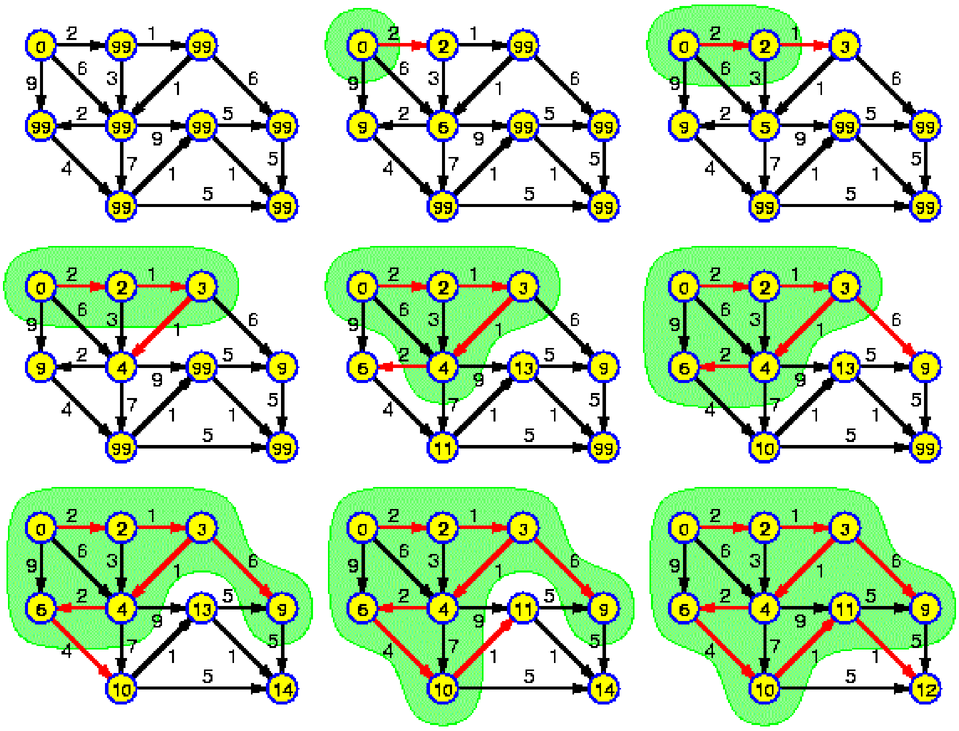


Figure A.2: Illustration for Dijkstra's algorithm. [95]

of the type of the application. There are four frequency bands that are allocated for the use of RFID [90]:

- Low Frequency (LF): 125 KHz - 134 KHz, and is used for near field communication applications, such as, access control.
- High Frequency (HF): 13.56 MHz, and is used for medium range communication applications or for applications which requires higher data exchange rate.
- Ultra High Frequency (UHF): 850 MHz - 950 MHz, and is widely used for applications that require long range communications.

More information on RFID, especially on UHF Passive RFID, is presented in Chapters 4 and 5.

A.3 Dijkstra Shortest Path Algorithm

Dijkstra's algorithm is a very widely used algorithm for computing the shortest path between source and destination nodes in a graph. The graph may represent a road network or a computer network for instance.

As depicted in Fig. A.2, the algorithm computes the shortest path between a starting node and an end node by firstly marking the distance or cost from the starting point to every other edge with infinity. This is to imply that those edges have not been visited yet. Now from the current edge, the cost to every other connected edge is updated. This is achieved by summing the cost between an unvisited edge and the value of the current one, and remarking the unvisited edge with the summed value, if the value is lower than its current value.

The process of updating neighbor edges is repeated until the destination node is marked as visited. Once this is done, the shortest path is determined by tracing the way back to the starting node.

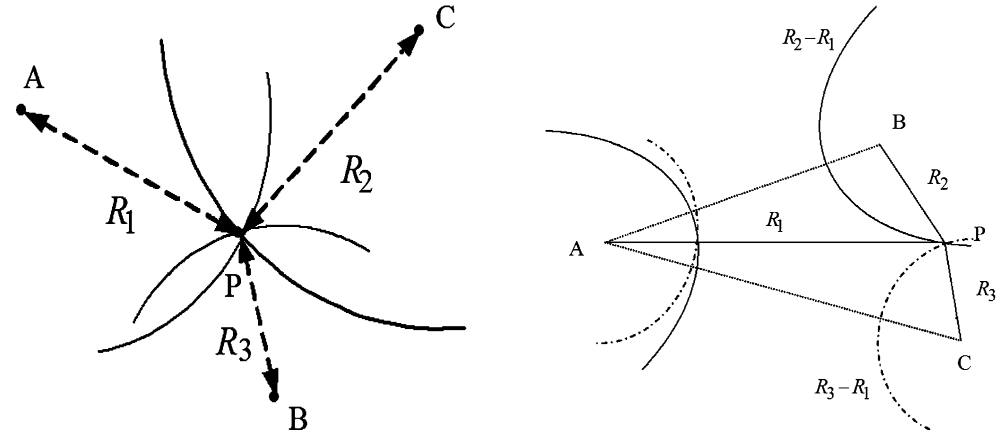
Appendix B

Indoor Navigation and Guidance Systems

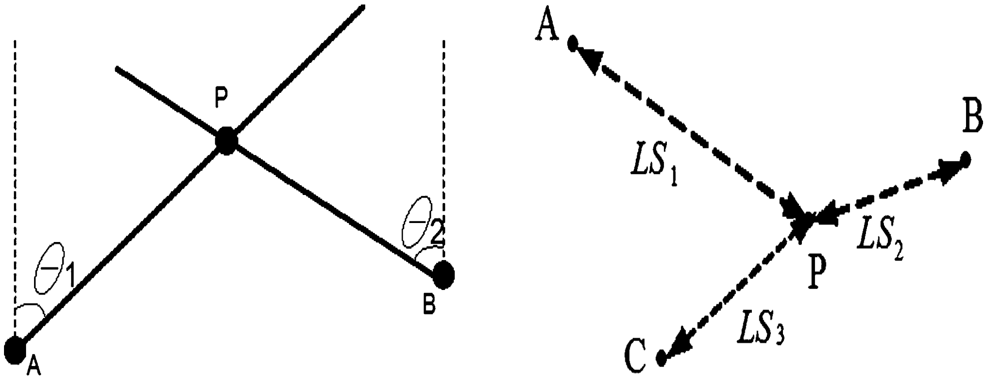
Global Positioning System (GPS) signals suffer from attenuation and has limited penetration capability indoors and therefore an alternative solution is dreadfully required [96]. In general, there are four categories of indoor localisation systems: Ranging (Distance-Based [97–99] and Angle-Based [100, 101]), Location Patterning [102–104], Inertial Sensors (INS) [105–107] and Cell of Origin [108–110]. The common technologies that adopt these groups, excluding the INS, are Wireless Fidelity (Wi-Fi) [111–113], RFID [114–116], ZigBee [117, 118], and Bluetooth [119, 120].

B.1 Ranging

Distance-Based systems are known to operate by the lateration technique. For instance, Time of Arrival (TOA) of signals transmitted from a mobile device to several receiving nodes, can allow the computation of the distances between the device and each of the nodes [121]. This can be achieved as the speed of radio propagation is known to be the speed of light. With distance used as radius, three



(a) Based on TOA measurements. **(b)** Based on TDOA measurements.



(c) Based on AOA measurements. **(d)** Based on RSSI measurements.

Figure B.1: Ranging-based positioning techniques. [124]

calculated distances from three nodes are sufficient to estimate the location of the device. Because TOA measurements require absolute synchronization between all the terminals, Time Difference of Arrival (TDOA) measurement technique can be used instead [122]. Another approach in lateration is converting the Received Signal Strength Indicator (RSSI) into distance. This is done by utilising radio propagation models [123]. On another side, the Angle-Based systems utilise the Angle of Arrivals (AOA) from three or more nodes to determine the position of the device [100, 101]. Illustration of the common ranging-based positioning techniques is shown in Fig. B.1.

B.2 Location patterning

Localisation by ranging has proven to be suitable for large and open spaces. However this is not the case in uncontrolled indoor environments where radio waves suffer from attenuation and multi-path effects, that will significantly alter a reasonable positioning estimate. Location patterning is hence commonly used to address these issues [102–104]. The process consists of the following: 1) calibration stage where several RSSI readings of a mobile device from multiple nodes at the target environment are sampled and recorded - forming a radio map. 2) Operation stage where the actual localisation occurs - a group of nodes (e.g. Wi-Fi access points) provide their RSSI measurements to the mobile device, the readings are then compared with the radio map and finally a deterministic or probabilistic algorithm will be utilised to estimate the target position.

B.3 Inertial sensors

On the other hand, the INS in smart phones can be utilised to capture and analyse the movements of the device holder [105–107]. The main components of the INS are accelerometer which measures the change in velocity in the 3 axis plane, gyroscope which senses the orientation and magnetometer which measures the direction of the magnetic field relative to earth [90].

Appendix C

iParker Appendix

C.1 G and NG Parking Methodologies

In this section we describe the methodologies for G and NG parkers to find a suitable parking space. The flow of these methods are implemented in code to allow the comparison with iParker, in Chapter 3.

- **Guided Parker Methodology**:

  As stated earlier in Chapter 3, G is modeled to be a smart parking system but without reservations, such that, parkers know about the real-time availability of parking resources, their pricing and their proximity to their targeted destination(s). As shown in Fig. C.1, a G parker's approach to find parking is as following: (1) Parker arrives to the vicinity of destination(s), which is defined as 10 minutes away from the destination(s). (2) Parker checks all the parking lots in his/her area for vacant spaces of his/her type (normal/disabled). (3) The walking and payment costs of the parking lots with vacant spaces are computed and compared with the parker's maximum tolerated costs. (4) If parker finds a suitable parking lot with a vacant space, he/she will travel to it. (5) Once the parker arrive to the parking lot, it may or may not contain a free parking space at this time. If the parking lot has a free space, the parker will park. If not, the parker will repeat the process starting at (2). However, this time, the parker will travel from a parking lot to another - not from vicinity of destination(s) to a parking lot. If the parker cruised for parking for longer than 30 minutes, they abort the searching process.

- **Non-Guided Parker Methodology**:

  For NG, parkers do not have any information about parking resources availability nor price information. In NG system, parkers will search for a free tolerated parking resource in an increasing radius method till they occupy it. As shown in Fig. C.2, a NG parker's approach to find parking is as following: (1) Parker arrives to the vicinity of destination(s), which is defined as 10 minutes away from the destination(s). (2) Immediately, parker travels to the first nearest parking lot. (3) Parker identifies/evaluates the type of parking space (normal/disabled), walking and payment costs of occupying a parking space in that car park and then matches that information with his/her maximum costs and type. (4) If the parker found the parking lot suitable for his/her budget and walking constraints, and a vacant parking space exists, the parker will park. Otherwise, the parker travels to the next nearest parking lot and repeat step (3). If the parker fails to find a vacant suitable parking space for longer than 30 minutes, the parker will abandon the parking process.

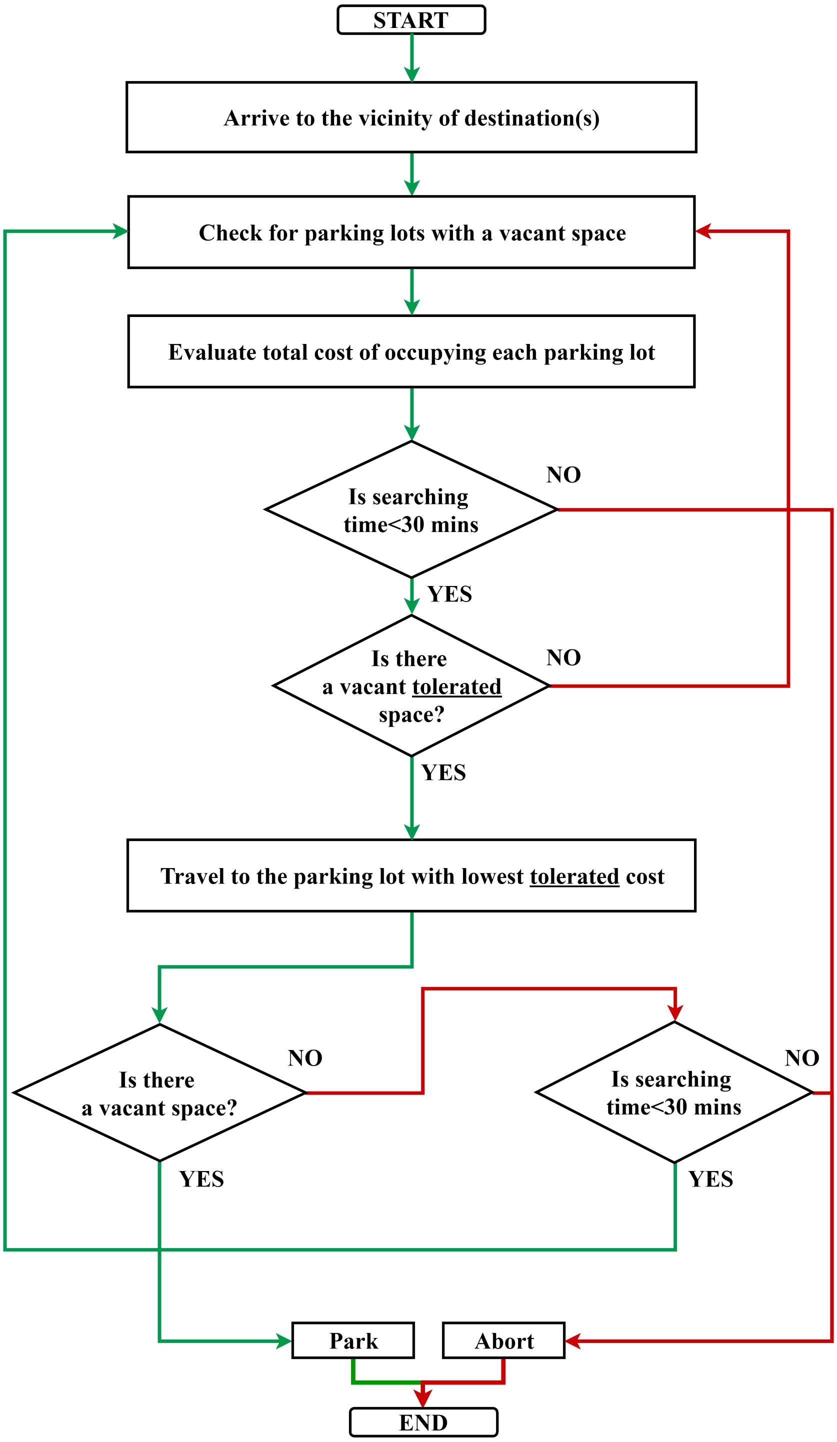


Figure C.1: Parking methodology flow for Guided parkers.

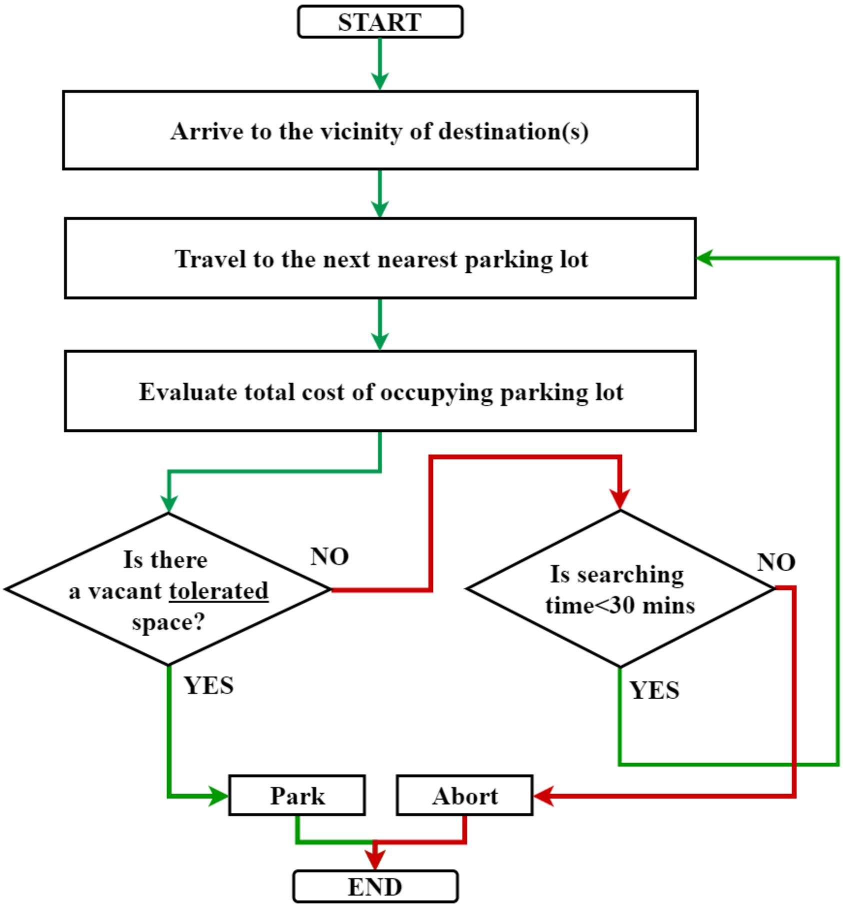


Figure C.2: Parking methodology flow for non Guided parkers.

Appendix D

INDO Appendix

D.1 SC, G, NG1 and NG2 Parking Methodologies

In this section we describe the methodologies for SC, G, NG1 and NG2 parkers to find a vacant parking space. The flow of these methods are implemented in code to allow the comparison with our smart commuting and parking system, INDO, in Chapter 4.

As mentioned in Chapter 4, parking behavior for the G, NG and NG2 are similar, such that users would scan the parking area in a sequential order until they find vacant spaces. In Fig. D.1, SC parker is the only parker who reach the destination using the shortest route; because he/she already knows where the vacant spot is. In addition, SC parker reaches the vacant space through the shortest path route using the route guidance in the INDO application.

On the other side, guided and non guided parkers (G, NG1 and NG2), search for a vacant space in a sequential order. Note that the order of these parking spaces is defined in the parking digital map, e.g., p1, p2, ..., pn.

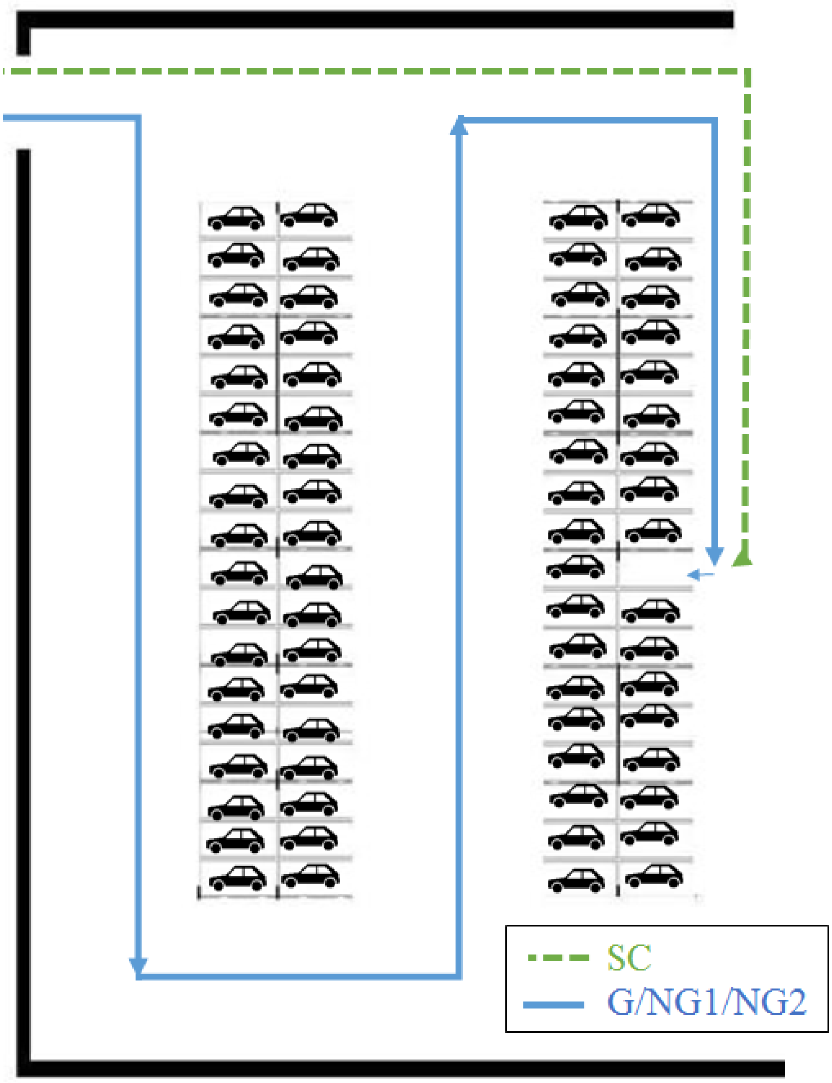


Figure D.1: Parking methodology comparison between SC and G, NG1 and NG2.

Appendix E

RFPark Appendix

E.1 Static Test Method

This section shows the combined requirements for the static testing of EPCglobal UHF RFID tags for their successful interrogation power based on 50% read rates. The test method discussed below is created to be a low cost alternative to the other standard test methods created by tag manufacturers [77].

E.1.1 Range Power Correction

Before obtaining any performance measurement, the testing equipment has to be calibrated and the Power Adjustment Factor has to be measured. In Fig. E.1, the experiment setup used for the following measurements is shown.

E.1.2 Procedure

- Set the reader transmission power:
  - Set transmit and receive attenuation to zero.
  - Set the reader transmission power to the 32 dBm or the maximum power.

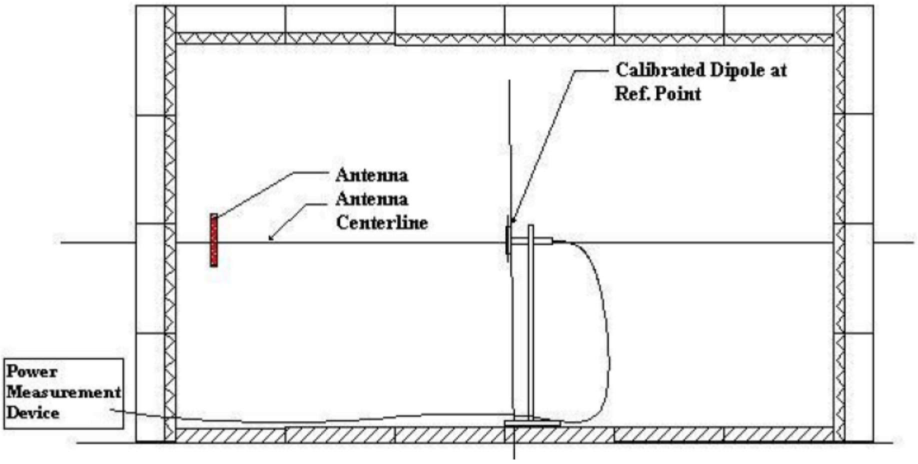


Figure E.1: Range setup for setting standard power. [77]

- Turn on the reader continuous reading.
- Place the dipole antenna at the reference point in the test range. Dipole antenna should be oriented vertically and the power measurement instrument should be placed outside of the test range.
- For better measurements if using a spectrum analyser, measure for 2 minutes while the reader is actively reading and set the display for maximum hold and peak detector.
- Finally, at each frequency take the analyser readings.
- Calculate cable loss to obtain the Power Adjustment Factor. See the next section for more information on how to perform the calculations.

E.1.3 Cable Loss and Antenna Factor Calculations

- Measure the peak power at the receiver (spectrum analyser) while setting the reader to maximum power.
- Subtract the gain of the dipole antenna from the measured power.

- Add the cable and connector loss to the previous result to obtain the power at reference point when the reader is set to maximum power.
- Repeat the previous procedure for each of the frequencies.
- Now the power adjustment factor is calculated as the measured power at reference point minus reader power setting.

E.1.4 Tag Minimum Turn on Power Measurement

Now it is possible to measure accurate data for tags performance. To Measure the minimum power needed by the reader to successfully read a tag, follow the steps below:

- Replace the dipole antenna with the tag at the reference point in the test range. The tag should be parallel to the reader antenna.
- Set receive attenuation to zero.
- Setup the reader to attempt interrogating the tag for 30 times.
- Record the number of successful reads of the tag EPC as a detection rate.
- Increase the reader transmit attenuation and repeat the previous steps until the tag detection rate falls to 50%. Notice that the reader must stop interrogation the tag for 500 ms between each attenuation level change to allow the energy stored of the tag to return to its minimal level.
- Record the reader transmit attenuation value when the tag detection rate falls to 50% as the tag minimum turn on power.

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