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Smart Parking: Network, Infrastructure and Urban Service

Trista Lin

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prepared at CITI-Inria Lab, DYNAMID and URBANET Teams

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Abstract

Smart Parking: Network, Infrastructure and Urban Service

Parking coordinates the land use and transportation in urban area, and it is also one of the most important assets, bringing revenue to city. As the increasing urban population, more and more cars, circulating through city, often get bogged down in traffic jam. 30% of traffic jam is caused by vehicles cruising for parking, said an economic expert. That is because drivers usually expect to get a cheap or free on-street parking place. Some French municipal statistics have shown that the wasted hours on parking search are at least 400 hours per day in city commerce district. If we convert those hours into fuel consumption, CO₂ emission and the economical effect, the parking is very expensive whatever from the personal, public or environmental viewpoints.

For this reason, if drivers can get the information of real-time parking availability, they will be able to adjust their traveling schedule without spending time cruising the city in vain. Smart parking, allowing drivers to access parking information through their smartphone, is proposed to ease drivers' pain. Many cities have been launching their smart parking projects and apps, yet still very few drivers can really benefit from them. That is because this technology still has to be improved from different perspectives: the robustness of sensor devices, the stability and timeliness of sensor networks, the quality and agility of urban service, and user-centric consideration. In addition, the smart parking deployment intends to deploy many sensors in the cities and overcome current sensor management problems. It can become a leading paradigm of smart cities and its extension. The work presented in this thesis sheds light on the deployment of smart parking system, with respect to sensor and service deployments.

First of all, we make a survey of the smart parking research and implementations, and then synthesize them into three different viewpoints. We cover global features of smart parking research by explaining how the parking information is collected, processed, and then distributed to drivers. After that, we provide a taxonomy with a detailed table to outline the existing research placement.

Next, we spotlight the manner to collect parking information. We begin by the multi-hop network architecture while deploying sensors on parking places, and how the network is formed by routing protocol. We then introduce the traffic intensity models by looking at the vehicle's arrival and departure probability, following the heavy-tailed distribution. We take the parameters from a real parking sensor network and evaluate them with different variations under two off-the-shelf medium access control (MAC) protocols. We test four different MAC protocols and different urban topologies with respect to the heavy-tailed traffic model. After that, we give an engineering insight and

summarize the relationship between the topologies and the MAC protocols.

When it comes to large-scale deployment, the network infrastructure is relevant. We study and introduce the deployment strategy of wireless on-street parking sensor networks. We define a multiple-objective problem with four objectives, and solve them with two real street parking maps. We present the results by showing the trade-off between minimum energy consumption, sensing information delay and the amount of deployed mesh routers and Internet gateways. The deployed mesh routers and gateways are the main cost, and the gateway is much more expensive than the mesh router. Thus, these results can be seen as a good guideline for designing and deploying roadside unit, to provide smart parking services to urban users. We also analyze these trade-offs to see how the different maps affect the optimal solutions.

In turn, merely the collection of parking information cannot ease drivers' headache. To provide good parking information to drivers, we begin by presenting the content-based Publish-Subscribe service system. We illustrate the system with a vehicular network and point out the importance of content and context. A message filtering is then proposed to match the parking information with users' interests. We propose an information, message and context to suggest each network device to make their own decisions of actions. We parameterize our analyzer to find the most suitable for our adopting network, and evaluate its performance with respect to the pure Publish-Subscribe service. Last, we also compare its satisfaction of users with the current mobile network.

In order to evaluate the resilience, we undertake the extended Publish-Subscribe model, and evaluate it under different unforeseen circumstances. We begin with a variable user participation rate, showing that the system can downgrade to one-hop communication. Then we also propose an offloading trade-off while the mobile network is too busy. Also, the information can be only disseminated to local drivers in vehicular network which lowers the parking conflicts.

Next, we begin with the formulation of on-street parking game. We evaluate the system with a variable user participation rate, showing that the system can downgrade to one-hop communication. Then we also propose an offloading trade-off while the mobile network is too busy. The information can be only disseminated to local drivers in vehicular network which lowers the parking conflicts.

To sum up, our work is based on the premise that large-scale parking sensors are deployed in the city. We look at the whole picture of urban service from viewpoint of the municipality. As such, we shed light on two main topics: the information collection on sensor deployment and an extended version of content-based Publish-Subscribe messaging paradigm. Our work gives a guideline from network-related perspectives for city before launching a smart parking or any similar real-time urban service. It also provides a meaningful evaluation platform for testing more realistic datasets, such as real vehicle traces or network traffic.

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Part I

Smart Parking solutions: An Introduction

Introduction

1.1 Motivation

As the urban population is increasing it brings the economic growth and the denser urban mobility. The first to be affected is the traffic. “30% of traffic jam is caused by vehicles cruising for parking” [2] is the most favorite citation while talking about traffic problem. A huge percentage of cruising drivers are either tourists or thrifty persons. Tourists are usually unfamiliar with their travelling cities. They can only search parking by their eyes and probably some limited information, such as parking signs. Thrifty persons prefer to look for free or cheap on-street parking places. They often drive slowly around their destinations until they find one parking place.

Gantelet *et al.* [3] provide some interesting parking facts in France. Shockingly, 100% of Parisien drivers and 67% of Lyonnais drivers ever abandoned their trips due to the annoying and endless parking search. For the rest who found their parking spaces, they might park their cars in unauthorized areas. Such a wilful parking behavior may stop other vehicles and frequently provoke traffic accidents. If we sum up all the wasted hours of parking search, there are at least 400 hours per day in city commerce district. If we convert those hours into fuel consumption, CO₂ emission, and the economical effect, the parking search is very expensive whatever from the personal, public or environmental viewpoints.

Belloche [4] studied the survey-based data in 10 different on-street parking areas in Lyon in order to model parking search time. It shows that congestion ratio is more relevant to calculate parking search time than parking occupancy rate. Turnover rate is certainly a promising factor as well since it correlates with parking policy. When congestion ratio is high, there are more potential parking competitors and cars move more slowly. If static or electronic parking sign is unclear or out of order, the traffic will be even more messy. Logically speaking, a hidden problem is never be shown in the survey but we all experienced it. That is we never see an extremely long parking search time from official statistics because they are not recorded by parking payment system. Most drivers choose to give up their trip or find an alternative transportation after spending a long period but finding nothing.

According to the above, if drivers can have the information of real-time parking availability, they will be able to adjust their travelling schedule without spending time cruising the city in vain. Many cities have been starting smart parking projects. *Smart parking is a way to help drivers find satisfied parking places efficiently through*

information and communications technology, especially for on-street parking. The initial idea of smart parking was proposed at least ten years ago, yet its development starts to flourish these five years. That is thanks to smartphone, many users can connect to Internet and search for information of traffic, transport, traveling, restaurant and accommodation anytime and anywhere.

In addition, cities deploy smart parking service on the basis of economical consideration. First, drivers can shorten the parking search time, reduce environmental pollution, consume less petrol and alleviate traffic congestion through the information from smart parking app. If drivers know there is no parking place around their destinations, they can also choose public transport. That increases the use rate of city facility and the city's revenue as well. Second, if drivers can find parking fast, the idle time of on-street parking is shorter and the parking revenue increases. Besides, installing sensors in frequent parked but unauthorized areas can detect illegal parking cars and get a penalty charge. Tahon *et al.* [5] gave a prediction figure in the city center of Ghent from 2010 to 2016. If a smart parking system is deployed, city's income from parking tickets and fines is in fact 10 times higher than the deployment cost. Similarly, the availability of electric vehicle and disabled parking stalls can also be highlighted for specific group of users. Third, once the traffic is fluent, it increases urban mobility and expand capacity of city. It also brings more population, activities and business opportunities.

Although there many deployment projects and apps, still very few drivers can really benefit from smart parking. For example, Nice is the first French city where a smart parking project was launched on 2012, named NICE PARK. Ten thousand sensors are planned to install in thirteen different parking areas. One smartphone app is developed so that drivers can check the information of parking availability from their phones. Parking sensors are connected to nearby multi-service parking meters. For those who do not own a smartphone, they can pay their parking places, get current parking availability in the city, and obtain information of tourism or public transport simply by multi-service parking meters. The deployment cost is estimated to be between 13 and 15 million euros. However, if we look at the users' comments on Appstore and Google Play, most of them are not satisfied at all, and even angry. Undoubtedly, the initiative of the project is good. But this technology still has to be improved from different perspectives:

- The robustness of sensor devices – Sensor devices are embedded systems which process sensed data into useful information and always evaluate their own health status, i.e., lifetime or malfunction, in order to inform system administration if there is any problem.
- The stability and timeliness of sensor networks – The sensed information on sensor devices has to be collected in storage, for example, parking meter, roadside infrastructure or central server. Hence, sensors are usually networked. When there are a lot of sensor devices, the spectrum is often limited and a transmission scheduling is needed. When a vehicle parks on sensor, it might block the radio communication and status change will not be broadcasted. The smart parking projects in San

Francisco and Los Angeles are both dedicated to shorten information transmission delay, i.e., 85% of events are received within 60 seconds.

- The quality and agility of city service – Smart parking system uses the sensed information to offer real-time parking information, named parking service, to drivers. The system has to manage all the parking resource, maintenance and payment. It has to efficiently filter parking information through driver’s interest and to deliver the most useful information to driver. If driver’s interest is not well defined, the system shall be able to adapt it and still provide a minimal level of service quality.
- The user-centric information dissemination – Currently all the smart parking apps provide the same information to all drivers. It happens often that there are more than two drivers chasing the same parking place. That is because the real-time parking availability data is useful only when the driver is very close to the parking location, said by Rajabioun *et al.* [6]. To avoid this problem, the information shall be diffused to drivers considering their mobility and location.

Moreover, the smart parking deployment intends to deploy many sensors in the cities and overcome current sensor management problems. It can become a leading paradigm of smart cities and its extension [7]. The work presented in this thesis sheds light on the deployment of smart parking system, with respect to sensor and service deployments. We review its main contributions in Section 1.2 and its organisation in Section 1.3.

1.2 Contribution

The main contribution of this thesis are resumed below:

- **Taxonomy of key findings of previous smart parking researchs.** We synthesize the global features of smart parking research obtained from previous works, studying or implementing different phases of parking problems. We then provide an overview and a taxonomy of the current smart parking research, concerning information sensing, service deployment and information dissemination. We also provide the information about the deployed network scale and the costs of some municipal projects. In addition, a detailed table, with respect to the taxonomy, is provided to describe the placement of smart parking research directions.
- **Evaluation of relevant bandwidth allocation methods under different urban topologies in wireless parking sensor networks.** We present the current feasible network infrastructure of parking sensor and then studies the vehicle inter-arrival and inter-departure times, following the heavy-tailed distribution, i.e., Weibull. These shape and scale parameters are gathered from the realistic deployments in Santander, Spain. By applying the traffic parameters, we compare the performance of two off-the-shelf bandwidth allocations and two of their hybrid version in three different kinds of urban topologies, i.e., crossroad, line and mesh. An engineering guideline is then given and can lead to important energy savings and shorten information delay while deploying wireless parking sensor networks.

- **Optimal deployment of urban roadside infrastructure to reveal the relationship between the cost and the network performance.** We formulate multi-hop networks according to multiple objectives, for example, network latency, energy consumption, deployment cost and sensor coverage. To examine our equations, we apply the maps of two Lyonnais areas and compare their impacts on our constraints. We indicate the trade-offs between the cost and the network delay and show the optimal results normally vary with the clustering features of city maps.
- **Proposal of an extended Publish-Subscribe messaging paradigm considering the quality of matched information to support smart parking service.** We introduce a content-based Publish-Subscribe service architecture and propose a message processing threshold based on the quality of the matched information. To test our model, we construct a dynamically moving environment. We first do the parameterization to choose the most suitable configuration. Then we evaluate it with respect to different amount of roadside infrastructure, i.e., grid size, and different ratio of parking demand to supply. The amount of transmission is also shown to see the network load. Even the service outperforms much better in mobile network than in vehicular network, our model can still improve the service spreading in vehicular network comparing with the pure Publish-Subscribe service.
- **Formulation of an on-street parking game.** We describe an on-street parking game by using drivers' parking choices, location and the amount of competitors. We also reveal the utility function of parking places from the viewpoints of drivers and city. Drivers' utility function is principally determined by their geo-location and the amount of competitors. However, from the municipality's viewpoint, if there are at least one competitor, namely more drivers know the parking place is available, the city has more chance to issue a parking ticket and increase parking revenue.
- **Analysis of drivers' impact on parking information dissemination on heterogenous networks.** We undertake the model we proposed in Chapter 5 and assess its robustness and resilience. We evaluate the user participation rate to see how the system reacts. Then we try to adapt our model in the heterogenous and give a trade-off of the percentage of network traffic between vehicular network and mobile network.

1.3 Organisation

This thesis is divided into seven chapters, forming four parts as follows:

First part of this thesis makes a survey of the smart parking research and implementations. It is divided into two chapters. In this chapter, we began with an introduction to the current problematic parking search. We introduce the motivation of our work and the concept of smart parking. We also remark the bottlenecks of the current parking system and then bring out our contributions.

Chapter 2 synthesizes the current smart parking research from three different viewpoints. We cover global features of smart parking research. We start by presenting an overview of smart parking technologies and its architecture, which allows us to explain how the parking information is collected, processed and then distributed to drivers. We then discuss all the related works on information sensing, service deployment and information dissemination in order to explain the context and the technologies we employ throughout this thesis. In the end, we provide a taxonomy with a detailed table to outline the existing research placement.

The second part focuses on the Network Perspectives on Urban Sensing, and the third part, the Network Solutions on Urban Service. They are dedicated to our contributions with complementary empirical and experimental studies. We organize the second parts into two chapters: Network protocols and deployment respectively to aim at the performance of parking sensor networks.

Chapter 3 begins by the multi-hop network architecture while deploying parking sensors in urban areas, and how the network is formed by routing protocol. We then introduce the traffic intensity models by looking at the vehicle's arrival and departure probability, following the heavy-tailed distribution. We take the parameters from a real parking sensor network and evaluate them with different variations under two off-the-shelf medium access control (MAC) protocols. We test four different MAC protocols and different urban topologies with respect to the heavy-tailed traffic model. After that, we give an engineering insight and summarize the relationship between the topologies and the MAC protocols.

Chapter 4 studies and introduces the deployment strategy of wireless on-street parking sensor networks. We define a multiple-objective problem with four objectives, and solve them with two real street parking maps. We present the results on the trade-off between minimum energy consumption, sensing information delay and the amount of deployed mesh routers and Internet gateways. The deployed mesh routers and gateways are the main cost, and the gateway is much more expensive than the mesh router [5]. Thus, these results can be seen as a good guideline for designing and deploying roadside unit, to provide smart parking services to urban users. We also analyze these trade-offs to see how the different maps affect the optimal solutions.

In turn, the third part is divided into two chapters. We shed light on an information-oriented service exploitation in dynamically moving networks. We propose an extended Publish-Subscribe service and discuss how its dissemination method can be impacted by the network in the two following chapters.

Chapter 5 is dedicated to the presentation of the content-based Publish-Subscribe service system. We illustrate the system with a vehicular network and point out the importance of content and context. A message filtering is then proposed to match the parking information with users' interests. We propose an information, message and context to suggest each network device to make their own decisions of actions. We

parameterize our analyzer to find the most suitable for our adopting network, and evaluate its performance with respect to the pure Publish-Subscribe service. Last, we also compare its satisfaction of users with the current mobile network.

Chapter 6 undertakes the extended Publish-Subscribe model, proposed in Chapter 5, and evaluate it under different unforeseen circumstances. We begin with the formulation of on-street parking game. Next, we evaluate the system with a variable user participation rate, showing that the system can downgrade to one-hop communication. Then we also propose an offloading trade-off while the mobile network is too busy. Also, the information can be only disseminated to local drivers in vehicular network which lowers the parking conflicts.

The last part of this thesis, Now and the Future of Smart Parking, draws some conclusions from our work. We also give our vision and some possible research directions in the near future.

A Taxonomy of Smart Parking Solutions

2.1 Overview of the research field

Parking have been the pain of all drivers and emerged as the research and industrial fields. Smart parking seems to be a feasible solution for our cities which integrates the knowledge from different disciplines. The technology for sensor and service deployments has been matured with a densification of large-scale deployment all over the world. We sketch the evolution of smart parking in Section 2.1.1 and reveal the provoking research directions. In Section 2.1.2, we propose a classification of the existing smart parking solutions and explain their corresponding disciplines. Finally, we outline the organisation of this survey in Section 2.1.3.

2.1.1 Causes of evolution

Since smart parking is proposed as the first solution to ease the increasing traffic congestion [8], many researchers and cities have been starting the service deployment according to different perspectives. An essential smart parking service includes two flows: information and traffic. The traffic flow happens on the pathway to find parking. Shown in the azure lower triangle in Fig. 2.1, normally, vehicle drivers receive parking availability information, steer to their desired parking areas and then park. On the basis of city infrastructure and communication technology, drivers might only get partial or outdated information and would have to repeat the parking search until they get one. When there are many drivers looking for parking, a competition occurs and results in cumulative parking conflicts. The parking behavior also varies considering the information that drivers have and how long they are cruising on the street. Once a vehicle arrives in or departs from a parking place, the parking availability information changes and has to be advertised to vehicle drivers looking for parking places. The information flow is shown in the upper pink triangle in Fig. 2.1. In order to get the occupancy status of parking places, fixed or mobile sensors are installed on street parking to detect vehicular events. Sensors then form a network and send the latest information to data storage devices. Drivers can obtain the latest information from variable message signs (VMS) or their handheld smart devices, which exchange messages with roadside infrastructure (RSI) or base transceiver stations (BTS).

Although there are many deployment projects and apps, still very few drivers can really benefit from smart parking. SFpark (San Francisco) and LA Express Park (Los Angeles)

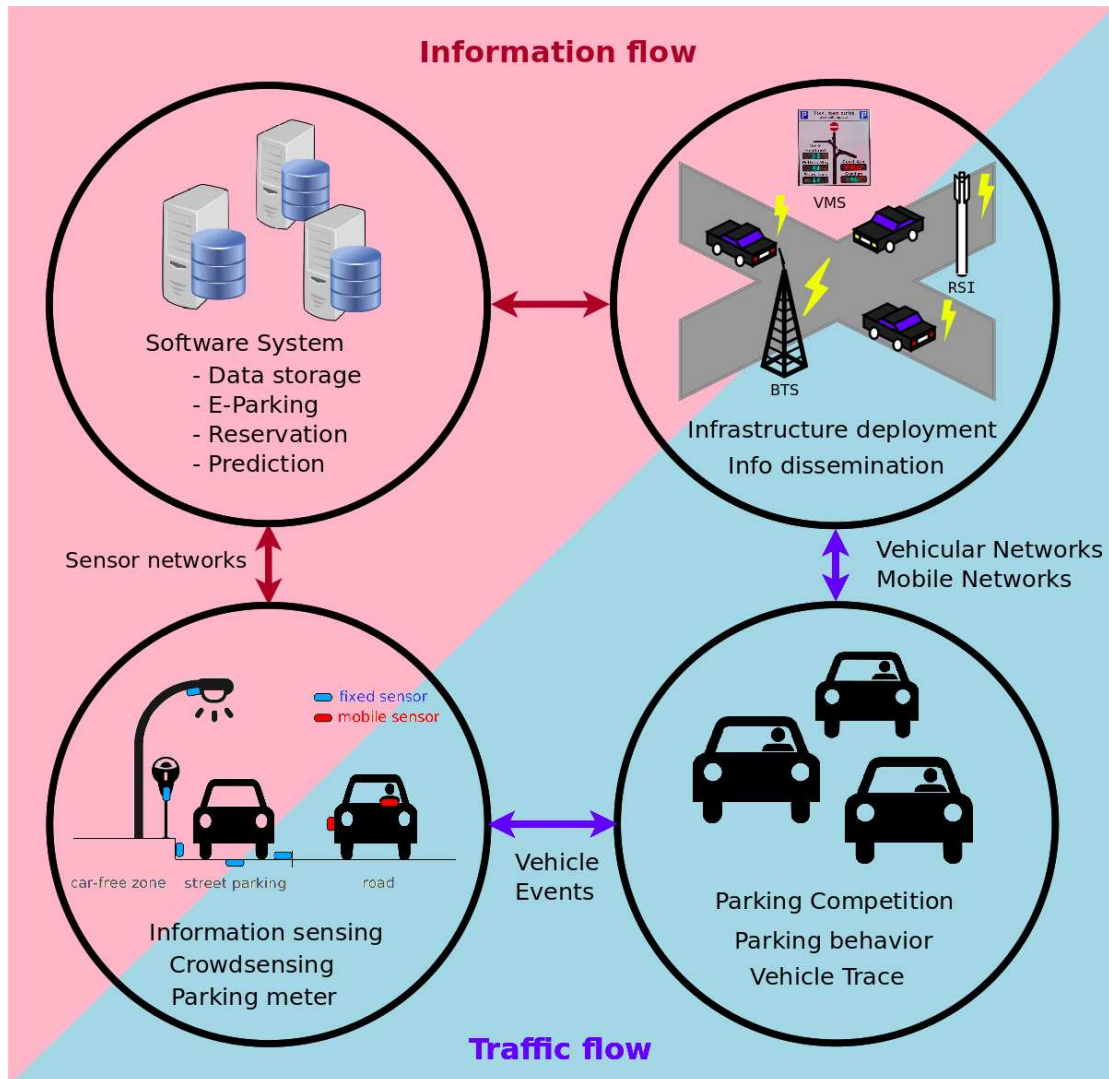


Figure 2.1: Smart Parking overview

are two most famous successful stories while talking about smart parking. But if we tried to deploy the same system in another city, it is always essential to make a preliminary test, choose the most suitable technology and then adjust the system according to the city street layout and inhabitants' habits. For example, Nice is the first French city where a smart parking project was launched in 2012, named NICE PARK. Ten thousand sensors are planned to install in thirteen different parking areas. One smartphone app is developed so that drivers can check the information of parking availability from their phones. Parking sensors are connected to nearby multi-service parking meters. For those who do not own a smartphone, they can pay their parking places, get current parking availability in the city, and obtain information of tourism or public transport simply by multi-service parking meters. The deployment cost is estimated to be between 13 and 15 million euros. However, if we look at the users' comments on Appstore and Google Play, most of them are not satisfied at all, and even angry. Undoubtedly, the initiative of the

project is good. But this technology still has to be improved from different perspectives:

- The robustness of sensor devices – Sensor devices are embedded systems which process sensed data into useful information and always evaluate their own health status, i.e., lifetime or malfunction, in order to inform system administration of any problem.
- The stability and timeliness of sensor networks – The sensed information on sensor devices has to be collected in storage, for example, parking meter, roadside infrastructure or central server. Hence, sensors are usually networked. When there are a lot of sensor devices, the spectrum is often limited and a transmission scheduling is needed. When a vehicle parks on a sensor-equipped parking place, it might block the radio communication and the status change will not be broadcasted. The smart parking projects in San Francisco and Los Angeles are both dedicated to shorten information transmission delay, i.e., 85% of events are received within 60 seconds.
- The quality and agility of city service – Smart parking system uses the sensed information to offer real-time parking information, named parking service, to drivers. The system has to manage all the parking resource, maintenance and payment. It has to efficiently filter parking information through drivers' interests and to deliver the most useful information to drivers. If driver's interest is not well defined, the system shall be able to adapt it and still provide a minimal level of service quality.
- The user-centric information dissemination and assignment – Currently all the smart parking apps provide the same information to all drivers. It happens often that more than two drivers chase the same parking place. That is because the real-time parking availability data is useful only when the driver is very close to the parking location, said by Rajabioun *et al.* [6]. To avoid this problem, the information shall be diffused to drivers considering their mobility and location.
- Uncertainty of drivers' behaviors and traveling traces – Drivers' information is essential to the parking system. A driver's behavior is strongly related to the information that (s)he has, personal preferences and the city street layout. Before getting the data of drivers, the drivers' behaviors can only be obtained from payment information or questionnaires. Thanks to the deployment of sensors in cities, scientists will start to analyze the measured data and re-produce them in a large-scale simulation.

Considering all the key factors identified above, the research of smart parking appears promising and beneficial to sustainable development of cities. The survey summarizing existing works will evolve into a useful engineering guideline in this transdisciplinary domain.

2.1.2 Literature classification

The literature on smart parking solution is very diversified. It not only balances land use and traffic, but also interfaces between inhabitants and urban resources. Parking

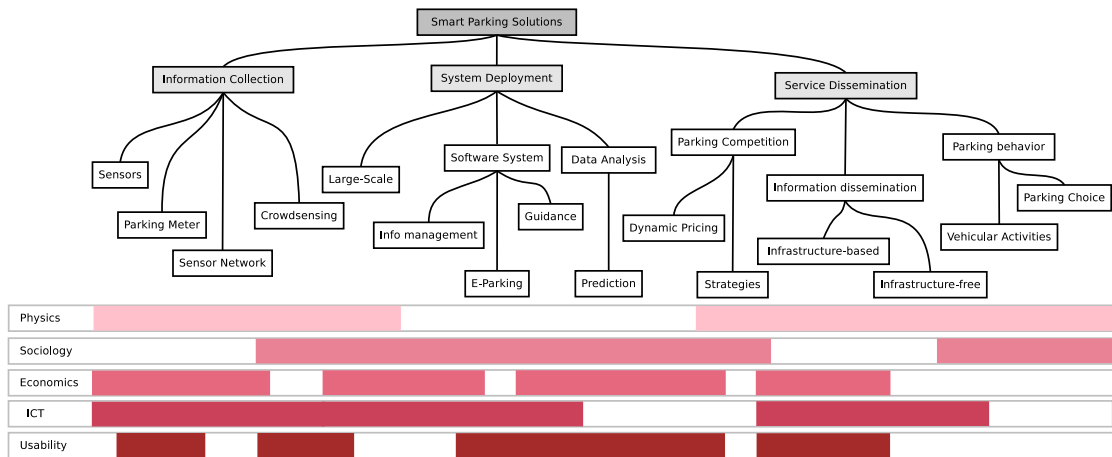


Figure 2.2: Proposed categories of smart city solutions and the spectrum of disciplines related to topics.

sensors collect information of inhabitants and store them in data center. Parking system analyzes the collected information and represents them to inhabitants to influence their traveling habits and decisions. City can hence reform its users by adjusting parking policy and the way to present information.

Harmonizing the relevant works in transdisciplinarity is not trivial. We finally decide to categorize them by their functionalities. The general outline of proposed classification is in Fig. 2.2. At the top level, we identify three macro-themes according the goals of the research fields: they manage information collection, system deployment and service dissemination. Within each macro-theme, a tree of sub-topics is germinated and developed. Next, we give an overview of the three macro-themes with all the topics addressed in our classification.

Information collection takes a technical overview on all the existing sensing techniques to identify status of parking places. Two major research focuses are on the identification and transmission of vehicular information. The former involves various stationary and mobile sensors, including their detection methods and installation. The latter explains how sensors and city infrastructure collaborate together to gather information efficiently.

System deployment deals with the exploitation of software system and statistical analysis of collected data. Software generally involves with E-Parking, reservation, guidance and a monitoring information for administration or often users. Then with the collected data, an analysis is often performed by data scientists to study the behaviours of drivers in order to improve the system performance and also help the municipality make a better urban planning.

Service dissemination investigates the relationship between the information and social features. Three major research focuses are information dissemination, parking

competition and parking behavior. Information dissemination is mainly related to the communications techniques between vehicles and information. The municipality can choose where and how to install urban infrastructure according to city's planning and budget. Parking competition always happens when more than two drivers contend the same parking place. With the information-assisted smart parking service, the decision of drivers is even more complicated to predict. Last, we also show some studies on parking behaviors which might be useful while designing a smart parking system.

The classification in Fig. 2.2 shows that all the sub-themes involve at least two disciplines by their nature. We can remark that smart parking research contributes highly on different interdisciplines and attracts a variety of participation on urban development.

2.1.3 Survey organisation

As previous mentioned, we introduce the smart parking solution on three different themes. We first start by explaining how to obtain parking information from different networked sensors in Section 2.2. Information collection is an important step to visualize vehicle's activities. It is also a converter between traffic and information flows. We discuss all the different sensors in Section 2.2.1 and the required network to gather their sensed information in Section 2.2.2. Parking meter is often the most important component of user interface. We also introduce some patents of parking meters in Section 2.2.3. For companies or academic projects, the deployment of large-scale sensor network is costly. Hence, we also introduce the crowdsensing method using in smart parking applications in Section 2.2.4.

Then, we introduce how to deploy smart parking service system considering different service types, for example, payment, monitoring, reservation, guidance, and information presentation, in Section 2.3. We start by the software system in Section 2.3.1. Drivers cannot only be guided or advised by smart parking system, but also reserve or pay their parking spaces through Internet. Then, we investigate the existing large-scale deployment projects and compare them with the technologies mentioned in Section 2.2 to see how cities adopt their smart parking solutions 2.3.2. To provide good quality of information and even to apply a better parking policy, the data analysis is often a must, like information aggregation and prediction. Section 2.3.3 presents some forecasting methods used in the current literature.

After that, we discuss how to how to spread information and the side effects in Section 2.4. The section often provokes the social analysis since the human activities are often difficult to capture and estimate precisely in the complicated real life with multiple information. Information dissemination is the first key point to influence traffic flow by information system. In Section 2.4.1, we show different information spreading ways according to city's infrastructure and sensor's transceiver modules. Drivers' mobility is also affected by the new information-assisted parking search. To improve parking occupancy and drivers' satisfaction, parking competition and driver's behavior are two major research themes. We present the current works on parking competitions

in Section 2.4.2. Some methods are proposed to ease drivers' conflicts. Section 2.4.2 is often linked with historical data mentioned in Section 2.3.3 depending if drivers have complete or incomplete information of the system. Later, we show some works on drivers' parking behaviors in Section 2.4.3.

Finally, we give a general overview on three different themes and conclude our works in Section 2.5. We also provide our insights and some perspectives on our contributions and the vast literature.

2.2 Parking information collection

Here, we introduce different types of sensors and the ways to deploy them. We also present some works on the network of sensors. Additionally, we reveal the detection manner of crowdsensing. More and more smart parking apps try to gather parking information without deploying thousands of sensors in urban areas.

2.2.1 Information sensing

Information sensing relies on sensors to collect the real-time parking availability information. Two types of collection methods are stationary and mobile. The former is to instinctively add the sensing ability on parking places. When the occupancy status changes, sensor can detect vehicle presence or absence and update the information in a short time, e.g., SFpark [9] in San Francisco allows that 85% of events are received within 60 seconds with its large-scale roadside parking sensor networks. The latter is to take advantage of vehicle's mobility to collect information along the route with fewer sensors. Mobile sensor can detect the occupancy status when it passes through the parking place, so the information might be updated for a long while, e.g., ParkNet [10–12] also in San Francisco. In ParkNet, taxi cabs collect data from GPS receiver and ultrasonic sensors and then transmit it over a cellular uplink to the central server. Such a mobile parking sensor system requires much less installation, yet needs a longer average inter-polling time, to wit, 25 minutes for 80% of the cells in business downtown area with 300 cabs. Several potential positions for installing sensors are shown in the bottom left circle in Fig. 2.1. Different sensors have distinct manners to detect vehicle presence. Table 2.1 gives a general idea of different types of sensors, and we explain them in detail as below.

Passive infrared sensor receives heat radiated from the human body and are often used collaboratively with other sensors [15; 16] to know if a driver parks and gets off his/her car. Active infrared sensor measures the distance to any obstacle in front [13; 17–22]. Infrared sensor is very sensitive to the sun and any kind of environmental object, so that the sensing accuracy is not so good. Similar to infrared sensor, ultrasonic sensor uses sound instead of light for ranging and works better in outdoor environments. Ultrasonic sensor provides a more complex signal pattern with a possibility of multiple detection in fixed [22; 33–35] or mobile [11; 62–64] scenarios. Accelerator measures the instantaneous ground vibrations. Since vehicles are usually the heaviest objects on the street, accelerator can infer that a vehicle comes and park, with the aid of other

Table 2.1: Different types of parking detection sensors.

	N^o	Sensors	IV	F	EI	SS	P	IS	CT	A	C	MD
Stationary	1 ^a , 1 ^p	Active ^a /passive ^p infrared [13–22]		√	√	√		*		**	*	√
	2	Accelerator [23]			√	√		*		*	*	√
	3	Magnetometer [9; 15–17; 22; 24–32]	√			√		**		***	**	
	4	Ultrasonic [17; 22; 33–35]		√	√	√		*		***	*	√
	5	Camera [36–48]		√	√	√	√	*		**	***	√
	6	Acoustic [22; 49]		√	√	√	√	*		*	***	√
	7	Optical [22; 23; 50–54]			√	√	√			**	*	
	8	Inductive loop [35; 55]	√					***	√	***	*	
	9	Piezoelectric sensor [14]	√		√			***	√	***	****	√
	10	RFID [30; 56–59], iButton [60]	√	√		√	√	**		***	**	
	11	Radar [61]		√	√	√		*		***	***	√
Mobile	12	Ultrasonic [11; 62–64]		√	√	√		*		***	*	√
	13	Laser rangefinder [65; 66]		√	√	√		*		***	***	√
	14	Smartphone (GPS, human, microphone, Bluetooth [67], Wifi [68], accelerator [69–71], magnetometer [72], QR code [73]) [74–80]		√	√	√	√	-		-	-	√
	15	Camera (on robot) [81]		√	√	√	√	*		*	****	√

† IV: intrusive; F: flexible; EI: environmental impact; SS: small size; P: privacy; IS: installation; CT: contact; A: accuracy; C: cost; MD: multiple detection

sensors, e.g., optical sensor [23], which detects the change in light. Optical sensor must be installed where the light can be obscured by a parked vehicle [22; 50–54]. However, the optical sensor is vulnerable to any light source and transient staying objects, so its accuracy is still questionable.

Magnetometer is so far the most common stationary parking detection sensors, especially for municipal deployment [9; 24–26; 51; 91–93]. It measures the current magnetic fields and detects the arrival of huge metal objects. Its signal pattern is easy to read and precise but cannot support multiple detection. It is also more expensive than the above mentioned sensors. Alternatively, [32] installed magnetometers along the driving pathway and compared the different counts between any two adjacent sensors to know roughly how many vehicles are parked between them.

Camera [36–39; 39–46; 48] and acoustic sensors [22; 49] provide a much more complicated signal pattern than ultrasonic. Both of them require image and sonar processing in order to extract the desired information from the background noise. Nevertheless, they have fastened certain research interests because of some extra information, concerning criminal scenes or personal privacy, might be retrieved from them.

Inductive loop and piezoelectric sensor are both contactive and installed on road surface. Inductive loop is a mature technology and widely used for traffic surveillance. It simply detects if a vehicle is passing [35; 55]. Piezoelectric sensor is similar to inductive loop but able to read more information from the pressure exerted on it [14]. Such kind of contact sensor requires an intrusive installation and are easy to be worn-out because of the frequent use.

RFID is often proposed in smart parking payment solution thanks to its identification tag. As the popularity of electronic toll collection (ETC), many vehicles,

Table 2.2: Smart Parking solution for information collection

	Reference	Info source		Deployment		Storage			Service			Parking game			Network			
		Type	S/P	NetS	NetU	C	D: $\frac{S}{V}$	D:I	AU	BC	EP	Rsv	UB	SG	PD	NP	OT	
Information sensing	B. Zhang [45]	5	1/6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	U-Park [15]	1 ^a ,3	2/2	802.15.4	-	-	-	-	-	-	-	-	-	-	-	-	-	
	Männi [16]	1 ^a ,3	-	802.15.4	-	-	-	-	-	-	√	√	-	-	-	-	-	
	Z. Zhang [27; 82]	3	82/82	802.15.4	-	√	-	-	-	MS	-	-	-	-	-	-	-	
	Abdullah [57]	10	-	802.15.4	-	√	-	-	-	MS	-	-	-	-	-	-	LT	
	PGS [29]	3	*/10	802.15.4	-	√	-	-	Pois(1)	MS	-	-	-	-	-	-	√	LT
	W. Zhao [30]	3,10	(40/40):2	802.15.4	Wifi,CN	√	-	-	-	MS	-	-	-	-	-	-	√	-
	Kianpisheh [35]	4,8	100/100	CB	-	√	-	-	-	MS	-	√	-	-	-	-	-	-
	Chinrungrueng [53]	7	2/1	WSN	Wifi,CN	√	-	-	-	-	-	-	-	-	-	-	-	-
	Boda [32]	3	11/72	-	-	√	-	-	171-183	-	-	-	-	-	-	-	-	-
	Sevillano [39]	5	-	-	-	√	-	-	-	-	-	-	-	-	-	-	√	-
	Nguyen [46]	5	-	-	-	√	-	-	≤5K	-	-	-	-	-	-	-	√	-
	COINS [48]	5	-	cable	-	√	-	-	-	MS	-	-	-	-	-	-	-	-
	SmartSpaces [17]	1 _a ,3,4	*/36	RF, Wifi	-	√	-	-	-	-	-	-	-	-	-	-	-	-
	Na [49]	5,6	35/35	802.15.4	-	√	-	-	-	-	-	-	-	-	-	-	-	-
Lee [22]	1 ^a -7	-	802.15.4	-	-	-	-	-	-	-	-	-	-	-	-	-	LQ	
WSN	Benson [83; 84]	3	5/5	nRF24L01	-	√	-	-	-	-	-	-	-	-	-	-	√	LQ
	Urdiain [18]	1 ^a	10/10	nRF24L01	-	√	-	-	-	-	-	-	-	-	-	-	-	√
	Bagula [58; 59]	4,10	13/*	802.15.4,CB	-	√	-	-	-	MS	-	√	-	-	-	-	-	√
	Lin [85-87]	3	*/12-120	802.15.4	-	√	-	-	-	-	-	-	-	-	-	-	-	√
	W. Chen [88]	3	-	WSN	-	-	-	-	-	-	-	√	-	-	-	-	-	√
Crowdsensing	ParkSense [68]	14	-	CN	-	√	-	-	-	-	-	-	-	-	-	-	-	-
	UPDetector [80]	14	-	Wifi,CN	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Villanueva [72]	14	-	Wifi,CN	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	VeLoc [70]	14	4/445	Wifi,CN	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Rinne [74]	14	*/138 areas	Wifi,CN	-	√	-	-	-	-	√	-	-	-	-	-	-	-
	X. Chen [75-77]	14	*/810	Wifi,CN	-	-	-	1K	-	-	-	-	√	-	-	-	-	-
	iPark (Yang) [78]	14	-	Wifi,CN	-	√	-	-	1G	-	-	-	-	-	-	-	-	-
	PocketParker [69]	14	105/*	Wifi,CN	-	√	-	-	-	-	-	-	-	-	-	-	√	-
	Kiffe [89]	14	*/ 6 zones	Wifi,CN	-	√	-	-	-	-	-	-	-	-	-	-	-	-
	ParkJam [79]	14	-	Wifi,CN	-	√	-	-	-	-	√	-	-	-	-	-	-	-
	Coric [62]	12	-	Wifi,CN	-	√	-	-	-	-	-	-	-	-	-	-	-	-
	TruCentive [90]	14	-	Wifi,CN	-	√	-	-	131	-	√	-	√	GT	-	-	-	-

†In the Type column: the type id is referred to Table 2.1.

†In the Info source columns: S/P is the ratio of sensors to parking places.

†In the Deployment columns: NetS is the network of sensors. NetU is network of users (CN: cellular network; CB: cable; BT: PLC: power-line communication).

†In the Storage columns: C is centralized. D is distributed (S/V/I: sensor/vehicle/infrastructure).

†In the Service columns: AU is amount of service users (Pois: poisson - unit: vehicles/minute), BC is broadcast (MS: variable message sign, VNT: vehicular network), EP is E-Parking (namely drivers can find parking through telephone or internet).

RSV: reservation.

†In the Parking game columns: UB is user behavior, SG is strategy (GT: game theory).

†In the Network columns: NP is network protocol, OT is others (LT: lifetime; SC: security; AG: aggregation; LQ: link quality; FW: framework; SA: search algorithm).

equipped with RFID tags, can be detected by RFID readers installed on parking places [30; 56–59]. Laser rangefinder is often used to build a 3D map, especially for robot’s perception. Laser rangefinder, normally installed on the top of vehicle, emits a laser beam and calculates the time of flight to measure the distances from different objects in order to know if there are parked vehicles [65]. Intelligent robots cruising on the street can also be used to recognize available parking places using camera [81].

Mobile crowdsensing via smartphone is the most economical way to obtain parking availability information from drivers themselves [74; 76–78]. However, it yields privacy issues if a smartphone automatically collects data from users according to his/her movement [69–71], Bluetooth connection [67], WiFi signature [68], 3D compass [72] or all of them [80], and then updates it in a public database. If users can choose to contribute information on mobile applications or not, the system will be sensitive to free-riders [75] and selfish liars [79; 94; 95]. QR codes might be installed on parking spaces and help drivers to identify and pay their parking places [73]. When a driver ends a parking session, the system will announce that this parking place is now available to drivers looking for parking. However, this system cannot control if drivers do pay their parking places since QR codes cannot detect the presence of vehicles.

2.2.2 Wireless sensor network (WSN)

Once networked sensors are installed on parking places, they can form a network to send out their messages. Two typical communication methods are short-range, such as 802.11ah, low-power WiFi or Zigbee. and long-range, like Sigfox or LoRa. The long-range communication benefits from the existing radio access network and can communicate with infrastructure anytime and anywhere. Short-range communication is often implemented by WSN where messages have to be re-transmitted several times via relays, for example, parking meters or other sensors, until they reach city infrastructure. The studies on WSN have been germinating since several years. But few of them have been evaluated in a urban parking context considering the constraints of lifetime, information delay and wireless link quality. Urdian *et al.* [18] tested the LEACH¹ routing protocol on the Arduino platform² which is used as the parking sensor. Benson *et al.* [83; 84] used the DSYS25³ sensing node to experience the packet delivery rate with parked vehicles. If either sender or receiver is covered by parked cars, communication reliability in the range of 0 to 5 meters is good. If sender and receiver are both covered by parked cars, no communication is possible. Karbab *et al.* [59] implemented a car park management system and compare the energy and cost efficiencies while deploying a WSN and serial connection. Bagula *et al.* [58] formulated the optimal placement of ultrasonic sensors in smart parking as an integer linear programming multi-objective problem. W. Chen *et al.* [88] adopted a smart energy-efficient sensor. While increasing the amount of sensor nodes, the authors showed that the smart sensor can consume fewer energy in a larger network scale. Lin *et al.* [87] also formulated the optimal placement of city

¹nms.lcs.mit.edu/projects/leach

²www.arduino.cc

³www.ucc.ie/en/media/research/misl/2004publications/sensys04barroso.pdf

infrastructure as a multiple-objective problem and solved it in real maps. Besides, the performance evaluation of schedule-, contention-based and hybrid bandwidth allocation methods is compared by implementing four different MAC protocols in street parking scenarios [85; 86].

2.2.3 Parking meter

An important element seldom studied in smart parking research is parking meter. Yet there are many companies working on the patents of parking meters for payment, for example, PhotoViolationMeter™ Solution [96] and IPS group [97]. Parking meter is used by municipalities as a tool for paying on-street parking. With the rise of networked sensors, parking meters are turned into parking helpers which establishes a link between drivers and parking data. Single-space and multi-space meters are the two main automated payment machines. Multi-space meter manages several parking meters and can provide more functionalities than single-space one. Thanks to the technology of WSN, introduced in Section 2.2.2, parking meters are often used as relays for parking sensors. Thus, parking meters are not only basic payment machines but also transceivers, which can be integrated to existing relays and infrastructure for any communications devices [98]. Duncan Solutions [99; 100] has the patents on the wireless communications and control system of parking meters. Parking meters might communicate with some mobile access points, such as taxis and buses, to enrich urban information and increase transmission opportunities [101]. Flextronics [102] has a patent on proposing a parking space finder in vehicular environment. A vehicular on-board unit (OBU) can communicate with roadside parking meters in order to gather availability parking information and find a parking place. IPS group attracts a lot of attention because of the famous smart parking project SFpark [9]. Drivers, who park their cars on on-street parking places, can easily extend their parking time and pay from Internet. The payment information will be updated and showed on parking meters [103]. Besides, parking meters have an internal clock and are able to turn off themselves during parking time so as to reduce energy consumption. Some big companies work on the service integration to enrich the functionalities of parking meters and their interaction with drivers, for example Xerox PARC [104].

2.2.4 Crowdsensing

Crowdsourcing has been using in some smart parking applications, especially in gathering the sensed available parking information from smartphone users. Thus, a new term *crowdsensing* is then proposed. The most common way is to design a smart parking app and motivate users to share information voluntarily, e.g., ParkJam [79]. Rinne *et al.* [74] presented the pros and cons of mobile crowdsensing. Three high-level conclusions can be drawn by mobile sensors: if there was still space in the area, if the area is full, or if the area should no longer be full. VeLoc [70] used accelerometer and gyroscope sensors of smartphone and the inertial data of pre-loaded maps in order to find the parking place.

PocketParker [69] detected user's movement and derived the status of parking or

unparking by the accelerometer and GPS. ParkSense [68] detected the WiFi beacons to derive if the driver is back to the car or if he is moving. UPDetector [80] (unparking/parking detector) detected driver's behavior according to many different sensors on the smartphone, accelerometer, bluetooth, microphone, gyro, GSP, WiFi, parking payment app, or user's manual input. Villanueva [72] introduced a vehicle detection method using the 3D compass of drivers' smartphone. Thus, smartphone can detect if the driver is parking and if there is any adjacent parked vehicle. Also, the 3D compass can sense available parking places in its vicinity.

X. Chen *et al.* [75–77] showed that crowdsourcing-based smart parking applications can provoke the following problems: the information accuracy, participation rate, and freeriders. TruCentive [90] is another crowdsourcing smart parking app. Authors implemented a game-theoretical framework which adjusts the bonus dynamically according to the fraction of honest players. Kifle *et al.* [89] proposed an crowdsourcing smart parking application UW-ParkAssist working with UW-Police. UW-Police provides expert data from police department and can override incorrect data in UW-ParkAssist to reinforce the reliability of the collected information.

Accordingly, to avoid uncertain artificial factors, Coric *et al.* [62] use ultrasonic sensor to collect street parking map, like ParkNet [10–12]. iPark (Yang *et al.*) [78] built a parking map from vehicular trajectories without real-time occupancy status.

2.3 Parking system deployment

System deployment is the main work of service providers. The user interface and information processing shall be adapted to the service type. Here, we divided the parking system deployment into three parts: software system, large-scale deployment and data prediction. Table 2.3 gives an outline on system deployment.

2.3.1 Software system

2.3.1.1 Information management

Software system is the interface between information and system users. We see that there are many works on software system because the interoperability of different systems is tough to handle. Several works began with building a software system for WSN-based smart parking system. WSN provides detected information to the smart parking system and shall be well managed in order to reply driver's parking request. Thus, a parking system to monitor and to process data is the first priority. Joseph *et al.* [54] proposed a WSN-based park system to monitor not only the occupancy status but also the health situation of sensor nodes. Drivers can get the billing information via SMS. Vishnubhotla *et al.* [34] introduced a parking vacancy monitoring system with a ZigBee⁴-based WSN for showing the parking status in the entrance. Tang *et al.* [52] designed a parking de-

⁴www.zigbee.org

Table 2.3: Smart Parking solution for system deployment

Reference	Info source		Deployment		Storage			Service			Parking game			Network		
	Type	S/P	NetS	NetU	C	D: _n	D:l	AU	BC	EP	Rsv	UB	SG	PD	NP	OT
Vishnubhotla [34]	4	6/6	802.15.4,CB	-	✓	-	-	-	-	✓	-	-	-	-	-	-
Tang [52]	7	80/80	802.15.4	-	✓	-	-	-	-	✓	-	-	-	-	-	-
BeeParking [60]	10	24/14	BT,CB	-	✓	-	-	24	MS	✓	-	✓	-	-	-	-
Gopalan [105]	fixed	-	802.15.4,CN	-	✓	-	-	-	-	✓	✓	-	-	-	-	FW
KATHODIGOS [106; 107]	3,5	2/unslotted	CB,WSN	-	✓	-	-	-	-	✓	-	-	-	-	✓	LT
Joseph [54]	7	-	802.15.4	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	LT
SensCity [108; 109]	3	-	WSN,GSM	Wifi,CN	✓	-	-	-	-	-	-	-	MAS	-	-	-
Yang [110]	7	-	802.15.4,Wifi	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	-
Calipso [111]	3	5/5	802.15.4	Wifi,CN	✓	-	-	-	MS	✓	-	-	-	-	-	-
Grazioli [112]	-	-	-	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	-
Souissi [113]	3	5/5	802.15.4	Wifi,CN	✓	-	-	-	-	✓	✓	-	-	-	-	-
Rico [114]	10	-	802.15.4	Wifi,CN	✓	-	-	-	-	✓	✓	-	-	-	-	FW
Suryady [115]	3	-	802.15.4	Wifi,CN	✓	-	-	-	-	✓	✓	-	-	-	-	-
Kumar [116]	1 ^a	4/4	802.15.4	Wifi,CN	✓	-	-	2	-	✓	✓	-	-	-	-	-
iParking [117]	3	2/80-90	RS232&485	Wifi,CN	✓	-	-	≥120	-	✓	✓	✓	-	-	-	FW
Venkateswaran [19]	1 _a	-	RS232	Wifi,CN	✓	-	-	-	-	✓	✓	-	-	-	-	SC
Ganchev [118]	fixed	-	-	Wifi,CN	✓	-	✓	-	-	✓	✓	-	MAS	-	-	SC
Inaba [119]	-	-	-	CN	✓	-	-	-	-	✓	✓	-	-	-	-	SC
Giuffre [7; 120]	fixed	*/30-150	-	Wifi,CN	✓	-	-	10-80	-	✓	✓	-	-	-	-	-
PSOS [121]	-	-	-	Wifi,CN	✓	-	-	-	-	✓	✓	-	-	-	-	FW
Niculescu [122]	-	-	-	Wifi,CN	✓	-	-	-	-	✓	✓	-	-	-	-	-
ParkinGain [123]	-	-	-	-	✓	-	-	-	-	✓	✓	-	-	-	-	-
Yao [124]	4	314/314	CB	-	✓	-	-	-	MS	-	-	-	-	-	-	-
Bechini [73]	14	-	-	Wifi,CN	✓	-	-	-	-	✓	✓	-	-	-	-	-
Rodier [125]	fixed	6/6	WSN	Wifi,CN	✓	-	-	-	MS	✓	✓	✓	-	-	-	-
SmartParking [14]	1 ^a ,9	*/100-2800	Wifi	802.11	✓	✓	✓	Pois(20)	VN	✓	✓	-	MC	✓	-	SC
Hong [47]	1 ^a	64/64	CB	-	✓	-	-	Pois(λ)	-	-	-	-	MC	-	-	-
Xerox PARC [104]	-	-	-	Wifi,CN	✓	-	-	-	-	✓	✓	-	-	-	-	-
Moini [63]	-	*/5 zones	-	-	✓	-	✓	-	MS	✓	✓	✓	-	-	-	-
Jun [126]	-	-	-	-	✓	-	-	-	MS	✓	✓	-	-	✓	-	FW
SPARK (Srikanth) [127]	3,4	*/20	802.15.4	GSM	✓	-	-	3	MS	✓	✓	-	-	-	-	-
Shin [128]	-	*/3500	-	-	✓	-	-	120K	-	✓	✓	✓	UF	-	-	-
ParkNet [10-12]	12	50-2000/2.8e5	Wifi,CN	-	✓	-	-	-	-	-	-	-	-	-	-	-
SFpark [1; 9; 129; 130]	3	11900/8200	WSN	Wifi,CN	✓	-	-	-	-	✓	-	-	DP	✓	-	-
LA ExpressPark [24; 31]	3	*/6300	WSN	Wifi,CN	✓	-	-	-	-	✓	-	-	MC,DP	✓	-	-
Area Verda [51]	3,7	*/50000	WSN	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	-
Nice Park [26]	3	*/10000	802.15.4	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	-
WSN-DPCM [50]	7	25/15	802.15.4	Wifi,CN	✓	-	-	-	-	✓	✓	-	-	-	-	-
SmartSantander [91]	3	400/400	Digimesh	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	-
SMART Loja [131]	3	3948/1974	Digimesh	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	-
Beijing [92]	3	*/20000	433MHz	-	✓	-	-	-	-	-	-	-	-	-	-	-
Moscow Fastprk [25]	3	*/50000	Sigfox	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	-
ParkRight London [13]	1 _a	3400/3400	Vodafone	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	-
Melbourne [93]	3	7114/7114	Vodafone	Wifi,CN	✓	-	-	-	-	✓	-	-	-	-	-	-
Pullola [132]	fixed	-	-	GPS	✓	-	-	Pois(λ)	-	✓	-	-	-	✓	-	-
Klappenecker [133]	fixed	*/1000	-	802.11	-	✓	✓	Pois(19.6)	-	-	-	-	MC	✓	-	-
Richter [134]	3	*/6215	WSN	Wifi,CN	✓	-	-	-	-	-	-	-	-	✓	-	-
Vlahogianni [135; 136]	3	253/253	802.15.4	Wifi,CN	✓	-	-	-	-	✓	-	✓	-	-	-	-
Zheng [137]	3	*/8200+7114	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-
E. Wu [138]	-	*/260 lots	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-
Rajabioun [6; 139]	-	*/1000	-	CN(4G)	✓	-	-	-	-	✓	-	-	-	-	-	-
Ji [140]	-	*/492	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-
David (Mobinet) [55]	8	*/2750	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-
Y. Wu [141]	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-
Demisch [142]	3	*/8200	WSN	Wifi,CN	✓	-	-	-	-	-	-	-	-	✓	-	-
Koster [71]	14	-	-	Wifi,CN	✓	-	-	-	-	✓	-	✓	MC	✓	-	-

†In the Type column: the type id is referred to Table 2.1.

†In the Info source counms: S/P is the ratio of sensors to parking places.

†In the Deployment columns: NetS is the network of sensors. NetU is network of users (CN: cellular network; CB: cable; BT: bluetooth; PLC: power-line communication)

†In the Storage columns: C is centralized. D is distributed (S/V/I: sensor/vehicle/infrastructure).

†In the Service columns: AU is amount of service users (Pois: poisson - unit: vehicles/minute), BC is broadcast (MS: variable message sign, VN: vehicular network), EP is E-Parking (namely drivers can find parking through telephone or internet), RSV: reservation.

†In the Parking game columns: UB is user behavior, SG is strategy (MC: Markov chain; MAS: multi-agent system; DP: dynamic pricing; UF: utility function). PD is prediction.

†In the Network columns: NP is network protocol, OT is others (LT: lifetime; SC: security; AG: aggregation; LQ: link quality; FW: framework; SA: search algorithm)

tection demonstration system with a IEEE 802.15.4⁵-based mesh network. Each parking place is equipped with a light sensor to detect toy car's presence in order to provide the real-time occupancy information. Yang *et al.* [110] designed a WSN-based smart parking which collects information totally wirelessly. User interfaces are developed on smartphone, central web-server and embedded web server to guide users where available parking place is. SensCity [108; 109] implemented a Machine-to-Machine (M2M) architecture including parking sensors and parking applications. To improve the intelligence of smart parking system, a Multi-Agent System is used and modeled in MOISE⁶. iParking [117] is a smart parking system which collects sensing information and then show the current occupancy status through a social network, Twitter. KATHODIGOS [106] proposed a central parking information system integrating with two different heterogeneous sensor networks, namely wireless networked magnetometers and wired cameras. Then the authors tried to improve the precision of information by using a fuzzy inference system [107]. Calipso [111] is an European FP7 project targeting the development of IP connected smart objects. It proposed an architecture including several low-power IP stacks for protocol optimizations. Some authors might propose a wire sensor network due to the bad link quality of low-power wireless communications. Yao [124] uses CAN bus to connect all ultrasonic parking sensors, and then provides a guidance service by outer screen and light indicators. SmartParking [14] addressed the software and hardware architecture for the smart parking service. Also, a birth-death stochastic process is modeled to predict the revenues and pricing plans. Hong [47] proposed a parking emulation platform for those who want to test their parking service with deployed sensors.

2.3.1.2 E-Parking

Once the data storage and information monitoring are done, city can provide urban services by using the data they own. Since drivers can get the parking information in advance, a reservation system is often proposed. Kumar *et al.* [116] also presented a Zigbee-based smart parking system provides parking monitoring, guidance and parking reservation. Inaba *et al.* [119] introduced a smart parking prototype system supported by the Japanese telephone operator NTT. Telephone users can find a parking place easily and make a reservation by using Internet. Rico *et al.* [114] proposed a smart parking system with the integration of different technologies. The system provided a reservation scheme and presented the process while coping with parking requests. Venkateswaran *et al.* [19] proposed a smart parking reservation system which can assist drivers to check the current status of their parked vehicles. Giuffre *et al.* [7] presented the architecture of intelligent parking assistance which targets current parking management solutions through a wireless sensing technology. From the example of smart parking, the quality of mobility in urban areas is improved. To improve the efficiency of smart parking system, some works proposed a method or platform to improve the system agility. Ganchev *et al.* [118] presented a parking locator service based on multi-agent system. Infostations are used to relay the information between a central server and user-end mobile devices.

⁵www.ieee802.org/15/pub/TG4.html

⁶moise.sourceforge.net

Gopalan et al [105] introduced an OSGi⁷-based middleware for the smart parking system. The authors show that OSGi helps in efficient daily communication, data storage and processing. Suryady *et al.* [115] introduced a smart parking system using cloud-based platforms. To achieve a rapid deployment, each gateway, collecting data from parking sensors, is equipped with a cellular upload link in order to store them on the cloud. ParkinGain [123] presents the concept of a smart parking application that helps drivers to find and to reserve parking places using their OBUs or smartphones. Since the cost of deploying smart parking technologies is not negligible, other value-added services can benefit from the smart parking technologies to create business opportunities. Bechini *et al.* [73] proposes to install QR codes on parking spaces. Drivers can scan the QR codes in order to pay their parking places. When a driver ends a parking session, the system will announce that this parking place is now available to drivers looking for parking. Authors then studied the relationship between drivers' parking requests and the current status of parking spaces. A full process from parking search, reservation, occupation, payment and release is discussed from the viewpoints of drivers, administrators and data scientists. This system is low-cost, but it cannot control if drivers do pay their parking places since QR codes cannot detect the presence of vehicles.

The user interface is an important factor to guide drivers to find a parking place by using smart parking system. If the interface is badly designed, drivers might not be aware of the smart parking service or be badly guided by inappropriate information. Souissi *et al.* [113] focused on the development of application layer, to wit, how to obtain the sensed information from parking sensors and how to present them on a webserver. BeeParking [60] adopted a portable identification device, iButton, which is similar to RFID tag. The pre-installed iButton probes, on parking places, identify parked vehicles and then show the ambient information on a beehive-like display, which might help drivers to understand easily the parking information. Rodier *et al.* [125] described a smart parking educational tool designed by ParkingCarma⁸ to facilitate system use. PSOS (parking space optimization service) [121] is an E-parking service including three different parts, that is, channel manager, integration manager and application coordinator, to deal with the interoperability between different devices. Grazioli *et al.* [112] proposed a smart parking online service system, including web and mobile applications for drivers, parking operators and controllers. Operators can draw parking areas with detailed information. Drivers can be guided to the most suitable parking area by describing their interests. Controllers can monitor all vehicles parked in their own area. Drivers can also share their knowledge about parking occupancy to add the crowdsensing to this system. For some countries, such as Singapore, the use of mobile phones or tables is strictly prohibited while driving. Niculescu *et al.* [122] proposed an intelligent driver assistant to help drivers find quickly suitable parking in Singapore. The driver assistant uses speech to interact with drivers and becomes an active helper during the navigation by checking periodically the chosen car park availability.

⁷www.osgi.org

⁸www.parkingcarma.com

Table 2.4: Smart Parking City Projects

Project	City	#Parking	Cost	App	Launched
Stadtinfo Köln	Cologne	16000	-	-	09/1996
MOBINET	Munich	2750	4M€	-	09/1998
SIMERT	Loja	1974	-	SIMERT Loja Ecuador	05/2002
Area Verda (22@)	Barcelona	50000	-	apparkB	04/2005
Cabspotting(ParkNet)	San Francisco	281364	400\$/veh	-	04/2006
PARK Smart	New York City	177	-	Parker	10/2008
SFpark	San Francisco	8200	23M\$	SFpark	04/2011
SmartSantander	Santander	400	8.67M€	SmartSantanderRA	06/2011
Parking in Melbourne	Melbourne	7114	537,817\$A	Street Parking	07/2011
WSN-DPCM	Madrid	15	3.3M€	-	10/2011
Nice Park	Nice	10000	13-15M€	Nice City Pass	01/2012
Smart Parking Pilot	Beijing	20000	-	-	03/2012
Stockholm Parkering	Stockholm	37000	-	P-Stockholm	05/2012
LA ExpressPark	Los Angeles	6300	18.5M\$	Parker, ParkMobile, ParkMe	06/2012
ParkRight	London	3400	889,395£	ParkRight	10/2012
Moscow Fastprk	Moscow	50000	-	Parking Moscow	11/2012
ParkChicago	Chicago	36000	153M\$ ^a	ParkChicago	04/2014
ParkBoston	Boston	8000	-	ParkBoston	01/2015
Berlin Pilot	Berlin	50-70	-	-	09/2015

^aTotal project 153M\$ for bus rapid transit and parking program

2.3.1.3 Guidance

Drivers using smart parking service always receive a lot of information. The guidance shall provide a driving path to several potential parking places to avoid if there is any parking conflict. Jun [126] presented active and passive parking guidance system and proposed a system framework for active parking guidance. Since parking guidance is often limited by the dynamically changing availability information and traffic jam, a negotiation flow is analyzed to reveal some important technological problems. SPARK (Srikanth *et al.*) [127] is a smart parking prototype with parking sensors, guiding node, information display and GSM device. The parking status is sensed by parking sensors and guiding node can make a reservation via GSM communication. The monitoring, reservation and guidance modules are implemented to help drivers find parking. Shin [128] studied a smart parking guidance algorithm using utility function of parking place. Each parking utility function is calculated from driving duration from current car location to a parking facility, walking distance from a parking facility to destination, parking cost, traffic congestion caused by parking guidance itself, and the degree of availability.

2.3.2 Large-Scale Deployment

Since parking is a city-level problem, a large-scale deployment is spreading in different cities. Three main kinds of city-scale deployments are mobile sensing, fixed-site sensing via short-range communication, and fixed-site sensing via long-range communication. The typical example of mobile sensing is the ParkNet [11; 12] which takes advantage of the Cabspotting trace [10] in San Francisco to install parking detection sensors on cabs in order to detect the available on-street parking spaces. Since each cab either cruises in the central business district (CBD) to find passengers or drives toward the destination of the current passenger, the CBD has more chance to provide accurate information in

the ParkNet. With 536 cabs, the successive location information can be updated within 60 seconds apart [11].

Fixed-site sensing requires the installation of fixed parking sensors on each parking place. Section 2.2.1 introduced many different types of sensors, and we know that most sensors are battery-powered and sometimes might be underground. To maximize the lifetime of sensor devices, short-range communication requiring less transmission power is often favorable. To ensure sensors' connectivity, urban infrastructure, such as Internet gateways and repeaters, has to be installed within sensors' communication range in order to gather the sensed information. The most famous project is SFpark [9], the smart parking municipal service in San Francisco covers 30% of street parking. Sensors and meters can both communicate wirelessly. One repeater at almost each intersection completes the wireless mesh networks [1]. 85% events can be received in the central server within 60 seconds. The main goal of SFpark is to guarantee a 75% occupancy rate in any parking area by a dynamic pricing policy. Millard-Ball *et al.* [143] took the project and evaluated its impacts of two first years. The results conclude that rate changes have helped achieve the city's on-street parking occupancy and reduced cruising by 50%. LA ExpressPark [24] cooperates with Streetline⁹ as the Park Smart pilot program¹⁰ in New York City. Streetline adopts a time synchronized mesh protocol (TSMP) [144] to allocate the bandwidth for each device according to an anticipated frequency-time schedule. The messages can be received by the gateway in about 6-7 seconds. LA ExpressPark also applies the dynamic pricing policy to achieve 10-30% of parking spaces being available throughout the day [31].

Nice Park [26] is the smart parking program launched in Nice, France. The wireless parking sensors detecting parking occupancy are provided by Urbiotica¹¹. Nice Park installed 68 multi-service kiosks from Finnish Ensto¹² to collect parking information, and also provide extra traveling information so that drivers can choose an alternative transport from their parking places.

Beijing also launched a smart parking pilot program [92] in 2012 and used Timeloit's parking sensors¹³ to transmit messages. 35% of street parking is covered in Beijing. The real-time parking information is currently used by the government to regulate the traffic, but is still not available for the public. Most Asian cities have very few street parking, like Beijing (only 5.1% parking are on-street) and Tokyo. Comparatively speaking, Los Angeles and San Francisco have 75.5% and 63% of street parking respectively.

WSN-DPCM [50] and SmartSantander [91] are both experimental platforms for deploying, analysing and reproducing different smart city technologies. WSN-DPCM [50] stands for the Development, Planning, Commissioning, and Maintenance for WSN in smart environment. It makes one smart parking demonstrator with 15 parking sensors

⁹ www.streetline.com

¹⁰ www.nyc.gov/html/dot/html/motorist/parksmart.shtml

¹¹ www.urbiotica.com

¹² www.ensto.com

¹³ www.timeloit.com/plus/view.php?aid=99755

in Madrid. SmartSantander [91] proposes an unique city-scale experimental research facility for different smart city applications. 400 Libelium¹⁴ parking sensors were deployed to test smart parking service via Digimesh communication. Repeaters and gateways are equipped with Digimesh¹⁵ and 802.15.4 radios in order to communicate with sensors or other 802.15.4 devices. Digimesh is a power-optimized protocol for peer-to-peer WSN and can let all WSN nodes sleep. SIMERT [131] is an integrated parking system being deployed in Loja, Spain since 2002. 3948 Libelium parking sensors communicate with routers and gateways through Zigbee 900MHz and Digimesh 2.4 GHz. Each parking is equipped with two sensors in order to detect parked vehicles. A parking application is designed to show the real-time parking occupancy information to drivers. Authors then introduced the network topology, protocols and firmware programming for large-scale sensor deployment. Àrea Verda [51] is deployed in Barcelona. Parking sensors update the information to Barcelona Serveis Municipals (B:SM) via parking meters which are connected with the existing fiber-optic network. Since 2014, 500 parking sensors equipped with long-range communication technology are testing as well.

Long-range communication technologies, namely cellular IoT, are designed for Low-Power Wide-Area Network (LPWAN). Because of its compatibility with the existing cellular network, no extra infrastructure is required. Two most famous standards are SigFox¹⁶ and LoRa¹⁷. Thanks to Worldsensing¹⁸, SigFox is already commercialized in smart parking market and used in some cities, e.g., Moscow parking¹⁹. SigFox is an ultra narrow band technology to send small-size messages with a very small bandwidth via cellular link. LoRa has a longer transmission range than cellular network and provides different energy classes for different applications' needs. LoRa targets a wide range of applications but is not very popular yet in smart parking deployment. Libelium has implemented LoRa on some of their products. Another option, Vodafone M2M²⁰, adopted by Smart Parking²¹, is deployed in London (ParkRight [13]) and Melbourne [93].

Table 2.4 gives some information of the budgets while deploying large-scale smart parking systems and services. Parkopedia²² also provides some street parking information via parking meters and some existing city resident parking maps.

2.3.3 Parking Vacancy Prediction

Except reservation, parking prediction is most common way to forecast the occupancy rate of parking. From the prediction, smart parking service can provide a possibility of getting a parking place to drivers. That allows drivers to organize their transport

¹⁴ www.libelium.com

¹⁵ www.digi.com

¹⁶ www.sigfox.com

¹⁷ www.lora-alliance.org

¹⁸ www.worldsensing.com

¹⁹ parking.mos.ru/en/

²⁰ m2m.vodafone.com

²¹ www.smartparking.com

²² en.parkopedia.com

before their departures or even during their trips. Many different prediction models can be used to forecast parking demands. Y. Wu [141] introduced five forecasting methods: parking generation rate, vehicle population, land use and traffic impact analysis, trip attraction based on origin-destination data, and multivariate regression based on historical materials. Considering the lack of parking data and deficient survey precision, vehicle population model is selected to predict the parking demand of center area in Changping town in China. Author shows a parking demand forecasting from 2011 to 2015 according to car and motorcycle populations. The parking demand is assumed to be directly proportional to vehicle population.

The most popular prediction theory undertakes a Poisson arrival process, and then predicate the system capacity by Markov Chain. Pullola *et al.* [132] modeled the availability of a parking lot by a Poisson process, and then proposed an algorithm to give the availability probability of each parking spot when s/he arrives. Klappenecker *et al.* [133] also presumed that vehicle's arrival follows a Poisson distribution and modeled the parking lot by a continuous-time Markov chains. Then, with the predicted occupancy status, each parking lot can provide cruising vehicles with the availability information via vehicular networks.

Some realistic datasets are collected from the large-scale deployments in urban areas. Vlahogianni *et al.* [135; 136] studied the on-street parking data from SmartSantander and showed that the occupancy and parking periods of four parking areas follow a Weibull distribution. Zheng *et al.* [137] analyzed two parking datasets from San Francisco (SFpark) and Melbourne and predicted the parking occupancy rate by three different methods, namely regression tree, neural network and support vector regression. X. Chen *et al.* [130] also studied the parking data from SFpark and tried to predict the parking occupancy status in order to provide a better service. Richter *et al.* [134] compared several different spatio-temporal clustering strategies by studying the parking availability data from SFpark project. Even the spatial and temporal clusterings cannot provide a more accurate fit than the 7-day model (from Monday to Sunday), they can reduce the required storage size. Demisch [142] also analyzed the parking data collected by smart parking meters. Since the lifetime of parking sensors is short, providing parking information on smart parking meters is essential, especially for the dynamic demand-responsive pricing. That is to say, city uses historical data to develop an estimation model to predict parking occupation and adjust parking rate based on a sensor independent rate adjustment model. Rajabioun *et al.* [6; 139] used real-time parking data from San Francisco and Los Angeles and then proposed a multivariate autoregressive model to predict the temporal and spatial correlations of parking availability. The prediction errors are used to recommend the parking location with the highest probability of having at least one parking spot available at the estimated arrival time. Ji *et al.* [140] collected the parking availability data in several off-street parking garages in Newcastle to investigate the changing characteristics of short-term available parking spaces. This forecasting model is based on the wavelet neural network method and compared with the largest Lyapunov exponents method in the aspects of accuracy, efficiency and robustness.

Besides, drivers' decision can also be influenced by the prediction. E. Wu *et al.* [138] proposed a cost model to influence user's parking choice. The cost model is based on a probability of parking successfully and distance from the current location. Since the successful parking probability varies with time, a probability estimation method is proposed by using remaining available space count. Koster *et al.* [71] used smartphones as parking detection sensors and then studied the traffic of NYC department in order to estimate the occupancy status of parking lot. Then to calculate the availability probability of each parking space, the estimator considered all the properties of parking spaces (shade, sun, garage and cloudy) to know if a space has a higher chance to be taken. The smart parking system can then use the information to recommend drivers the most favorable parking place. David *et al.* [55] designed an event-oriented forecasting model as part of MOBINET project²³. The forecasting model considers the detected information (mainly for off-street parking) and estimated information from the online traffic data (mainly for on-street parking).

2.4 Parking service dissemination

In the end, we will introduce how to disseminate the parking information and how drivers react according to the information they receive. We divide service dissemination into three parts as well: information dissemination, parking competition and driver's behavior, and dedicated in 2.5.

2.4.1 Information Dissemination

In Section 2.3.2, all the existing large-scale deployment adopts a centralized method to provide parking information via cellular link or WiFi. Fig. 2.3 shows the classification of different parking information dissemination.

Except the existing cellular network and WiFi, a centralized information flow supported by roadside infrastructure and vehicular network is also very common. CBPRS [170], namely city-based parking routing system, proposed a centralized parking system which links intelligent lampposts and parking sensors by power-line communication. The central parking service run an ant colony optimization (ACO) to guide drivers from their current locations to parking places. The results show that ACO outperforms the Dijkstra's algorithm in reducing the traffic congestion and increasing the city flow. Moini *et al.* [63] evaluated the impact of the parking guidance system by varying its market saturation rate and car park demands. The results show that the popularity of parking guidance system can really ease the pain of finding parking in urban areas. SmartPark [145] used TinyNodes²⁴ as parking sensors. Sensors send periodically available parking information to vehicles so that vehicles can find parking places from nearby ones. Alhammad *et al.* [149] also proposed a smart parking based on sensing vehicles. The difference is that plenty of infostations are installed for each parking area

²³www.mobinet.de

²⁴www.tinynode.com

Table 2.5: Smart Parking solution for service dissemination

Reference	Info source		Deployment		Storage		Service			Parking game			Network			
	Type	S/P	NetS	NetU	C	D: $\frac{S}{I}$	D:I	AU	BC	EP	Rsv	UB	SG	PD	NP	OT
SmartPark [145]	3	25/25		XE1205	-	S	-	2	VN	√	-	-	-	-	-	-
Lochert [146]	3	*/real map		802.11	-	S	-	10K	VN	-	-	-	-	-	-	AG
SPARK (Lu) [147; 148]	12	*/1000		802.11	-	V	3	Pois(6)	VN	√	√	√	-	-	-	SC
Alhammad [149]	12	-		802.11	√	-	√	-	-	√	√	-	-	-	-	-
Bessghaier [150]	12	-		802.11	-	V	-	<300	VN	-	-	-	MAS	-	-	-
edPAS [151]	mob	*/50000		802.11	√	-	1000	100K	-	√	-	-	SH	-	-	-
Panayappan [152]	mob	-		802.11	-	-	√	-	-	√	-	-	-	-	-	SC
iPark (Zhao) [153]	mob	*/2000		802.11	-	V	-	<2K	VN	√	-	√	-	-	-	-
Delot [154-158]	14	*/60		802.11	-	V	-	60-240	VN	-	√	-	-	-	√	-
Kokolaki [94; 95; 159; 160]	fixed	*/25		802.11	√	S	-	5-70	VN	-	-	√	-	-	-	-
Tasseron [161]	3.14	*/96		S2V, V2V	-	S, V	-	≤96	VN	-	-	√	-	-	-	-
Caliskan [162; 163]	fixed	*/~129-70		802.11	-	V	129	10K	VN	√	-	-	MC	√	√	AG
Hornig [164; 165]	-	*/200-1200		802.11	√	-	100	300-1.8K	VN	√	-	-	CA	-	-	-
PMNET [20; 21]	1 ^u	-		802.11	-	-	√	-	VN	-	√	-	-	-	-	-
Vaghela [166]	-	-		802.11	-	-	100	100	-	√	-	-	AD	-	-	-
Kim [167]	-	-		VLC	-	-	-	-	VN	-	-	-	-	-	-	LQ
PhonePark [67; 168; 169]	14	*/16	BT	802.11	-	V	-	-	VN	√	-	-	-	√	-	-
Wang [23]	2.7	*/real map	802.15.4	Wifi, CN, BT	√	S	-	Real trace	VN	√	√	-	-	√	-	-
CBPRS [170]	fixed	-	WSN	802.11, PLC	√	-	√	7.5K-10K	VN	√	√	-	ACO	-	-	-
Geng [171]	3.5	*/2611	WSN	802.11, CN	√	-	-	Pois(0.4)	MS	√	√	√	-	-	-	-
Draskovic [172]	3.4	-	WSN	BT	√	-	-	-	-	√	-	-	ES	-	-	-
Zoeter [31]	3	*/6300	WSN	Wifi, CN	√	-	-	-	-	√	-	-	MC, DP	-	-	-
Millard-Ball [143]	3	11900/8200	WSN	Wifi, CN	√	-	-	-	-	√	-	-	DP	√	-	-
Song [173]	-	-	-	-	-	-	-	-	-	-	-	-	GT	-	-	-
Verroios [64]	12	-		802.11	-	V	-	20 veh/km	-	√	-	√	CT, TSP	-	-	-
Ayala [174-177]	12	*/20-80		802.11, CN	√	V	-	40-80	-	√	-	-	GT, SM, GPA	-	-	-
Chou [178]	-	-		802.11, CN	√	-	√	-	-	√	√	√	MAS	-	-	-
Dell'Orco [179; 180]	-	-		-	-	-	-	-	-	-	-	√	MAS, FZ, DP	-	-	-
Karaliopoulos [181-183]	-	-		Wifi, CN	√	-	-	-	-	√	-	√	GT	-	-	-
Di Napoli [184]	10	-		Wifi, CN	√	-	-	-	-	√	√	-	MAS	-	-	-
Schlote [185]	-	*/100-160		Wifi, CN	-	-	√	Pois(6)	VN	-	√	-	SH	√	-	-
Jin [186]	-	-		-	-	-	√	1500	-	√	√	-	SH	-	-	-
PFLBS [187]	-	*/73+32		-	-	-	√	-	-	√	-	-	FZ	√	-	-
Teodorović [188]	-	*/100-350		-	-	-	-	-	-	-	√	-	FZ, DP	-	-	-
Sarasua [189]	-	*/5567		-	-	-	√	5567	-	√	√	-	HTA	-	-	-
CGPS [190]	mob	*/20-80		802.11	-	V	-	25-85	-	√	-	√	GT	-	-	-
Doulaims [191]	mob	-		802.11	√	-	√	-	-	-	√	-	MIS, DP	-	-	-
Mei [192]	fixed	-		-	-	-	-	-	MS	-	-	√	GA	-	-	-
Caicedo [193; 194]	3	*/~600		-	-	-	-	Pois(38-98)	-	-	-	√	-	√	-	-
PARKAGENT [195]	-	*/10340		-	-	-	-	11.6K	-	-	-	√	MAS	-	-	-
Jossé [196]	-	*/5-20		-	-	-	-	100	-	-	-	√	-	-	-	SA
H. Guo [197]	-	*/800		-	-	-	-	<2K	-	-	-	√	CA	-	-	-
L. Guo [198]	-	*/113+526		-	-	-	-	≤800	-	-	-	√	-	-	-	-
Ma [199]	-	*/604		-	-	-	-	-	-	-	-	√	-	-	-	-
M. Chen [200]	-	*/188		-	-	-	-	-	-	-	-	√	-	-	-	-
Nurul Habib [201]	-	-		-	-	-	-	46K	-	-	-	√	-	-	-	-
Glasnapp [202]	3	*/6300	WSN	Wifi, CN	√	-	-	-	-	√	-	√	DP	√	-	-
Chaniotakis [203]	-	-		-	-	-	-	397	-	-	-	√	-	-	-	-
Yu [204]	-	-		-	-	-	-	-	-	-	-	√	-	-	-	-

†In the Type column: the type id is referred to Table 2.1.

†In the Info source columns: S/P is the ratio of sensors to parking places.

†In the Deployment columns: NetS is the network of sensors. NetU is network of users (CN: cellular network; CB: cable; BT: bluetooth; PLC: power-line communication; VLC: visible light communication)

†In the Storage columns: C is centralized. D is distributed (S/V/I: sensor/vehicle/infrastructure).

†In the Service columns: AU is amount of service users (Pois: poisson - unit: vehicles/minute), BC is broadcast (MS: variable message sign, VN: vehicular network), EP is E-Parking (namely drivers can find parking through telephone or internet). RSV: reservation.

†In the Parking game columns: UB is user behavior, SG is strategy (ACO: ant colony optimization; AD: agent discovery; CA: cellular automata; CT: clustering algorithm; DP: dynamic pricing; ES: Expert System; FZ: fuzzy logic; GA: genetic algorithm; GPA: gravity-based parking algorithm; GT: game theory; HTA: Hitchcock transportation algorithm; MAS: multi-agent system; MC: Markov chain; MIS: maxima interval scheduling; SH: scheduling algorithm; SM: stable marriage; TSP: travelling salesman problem). PD is prediction.

†In the Network columns: NP is network protocol, OT is others (LT: lifetime; SC: security; AG: aggregation; LQ: link quality; FW: framework; SA: search algorithm)

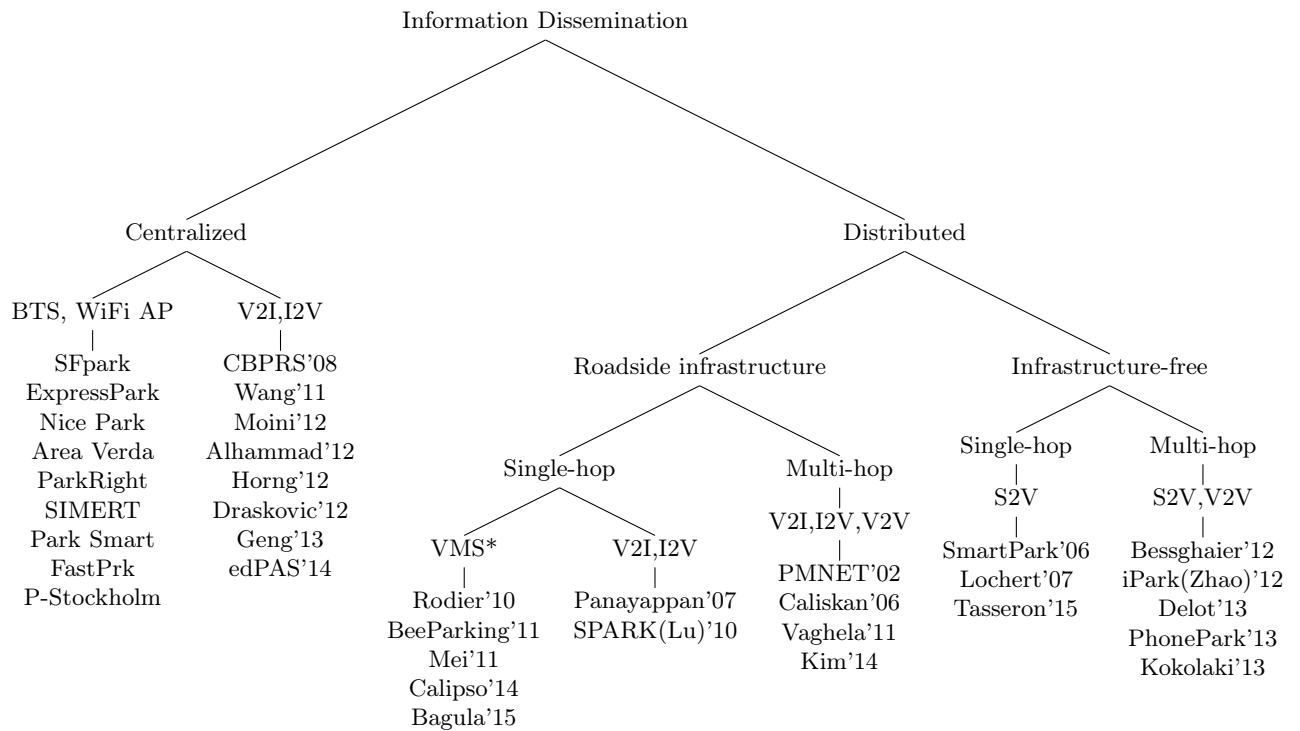


Figure 2.3: The diagram of parking information dissemination classification. BTS: base transceiver station; AP: access point; V2I: vehicle-to-infrastructure; I2V: infrastructure-to-vehicle; V2V: vehicle-to-vehicle; S2V: sensor-to-vehicle; V2S: vehicle-to-sensor; VMS: variable message sign.

in order to gather/provide information from/to vehicles. Horng *et al.* [164] proposed a V2I communication model between roadside infrastructure and vehicles to deal with parking demands. A cellular automata mechanism is used to describe the car society under a smart parking environment so as to allocate parking places more efficiently. Wang *et al.* [23] proposed a smart parking reservation system in an half distributed manner. Drivers get parking information from the central server but reserve their parking places directly with the nearby parking places. To test this system, the authors used a real-world traffic trace to generate the parking demand. The authors took a general assumption that real total traffic for parking is proportional to the highway traffic, and then classified the total highway traffic into incoming traffic and outgoing traffic, which represent that traffic approaching to and leaving from the target area. The incoming traffic serves as the reference of parking demand. After that, a real-world map in Los Angeles Downtown is imported into the simulator for the calculation of distance and path. Geng *et al.* [171] formulated a mixed-integer linear programming problem for smart parking demands and solved it with an optimal parking allocation method. Draskovic *et al.* [172] introduced a smart parking system using search algorithm to find the most suitable parking spaces as soon as possible.

Since the information delay caused by network retransmission is somehow long, the distributed information system is considered as an appropriate solution to reduce the network distance and network traffic. VMS is an instinctive way to indicate the vicinal

available parking information to drivers. Here, we classified VMS as distributed manner because VMS only shows the information in a certain nearby area. Alternatively, drivers can also receive information from roadside infrastructure in one-hop. Panayappan *et al.* [152] proposed a VANET-based infrastructure to provide available parking information, thus the deployment of roadside units is very important in order to cover each public or private parking area. Each vehicle can detect the occupancy status and send it to the roadside units. Each vehicle can also get the update occupancy from roadside units. The data storage is distributed among different roadside units which can be better protected to avoid some security problems.

To extend the information popularity (more accessible), messages can travel for more than one-hop from infrastructure in order to reach some vehicles which are not in the transmission range of the city infrastructure. We have seen the importance of parking meters for the industrial cycles in Section 2.2.3. Most vehicle-to-vehicle communications can benefit from these existing roadside parking meters to increase their packet transmission rates. Caliskan *et al.* [162; 163] presented a decentralized parking discovery method supported by automats, namely roadside parking payment terminals. Since automats deal with the payment, they also has the current occupancy information and can broadcast available parking information to vehicles periodically. Each vehicle aggregates received information before it distributes it to other vehicles. Vaghela *et al.* [166] also used parking meters (automat) to distribute parking information for passing vehicles. PMNET [20; 21] means parking meter network. Infra-red sensor is installed on parking meter to detect the occupancy status, and then parking meter can announce the available parking information via direct communication with vehicles. Vehicles can also forward this information to farther vehicles for increasing the parking usage rate. Another new highly anticipated technology is visual light communication (VLC) which exchanges message through light. The VLC module includes a LED as a light transmitter and a photo detector as a light receiver. Since light travels in straight lines, the VLC modules can communicate in the light-of-sight. Kim *et al.* [167] proposed a smart parking information system supported by VLC. Authors installed these VLC modules on vehicles and in the entrance of parking lots, and then drivers can obtain parking information while passing the entrance. The packet reception rate is about 80% and the transmission range is limited to 1.7 meters.

However, the installation of urban infrastructure is costly, so that vehicles can also choose to communicate directly with the sensors themselves. Lochert *et al.* [146] implemented an aggregation mechanism for data dissemination in vehicular networks. A real map is taken and TinyNodes parking sensors are supposed to be deployed on it. Similarly to [145], the parking availability information is broadcasted periodically. SPARK (Lu *et al.*) [147; 148] proposed that sensor-mounted vehicles can sense the parking status and disseminate it by their owns. Tasseron *et al.* [161] compared two kinds of sensing methods in vehicular networks: sensor-to-vehicle (S2V) and vehicle-to-vehicle (V2V). In S2V scenario, sensors are installed on parking places and transmit the occupancy status to nearby vehicles. In V2V scenario, vehicles can detect their own status (parking or unparking) and send the information of an available parking place

while unparking. The results show that S2V can improve the parking search efficiency under almost all conditions. V2V can only outperform S2V in situations with almost full on-street occupancy levels.

As previously mentioned, multi-hop can increase the information popularity. Bessghaier *et al.* [150] studied a full-distributed inter-vehicular network to see if the parking search time decreases, compared to the current blind search. edPAS [151] stands for event-driven parking allocation system. Drivers can subscribe to an event place and then get the update from communicators if there is any change on the information they ask for. Authors compared two different parking demand allocations: first come first serve (FCFS) and priority (PR). The results showed that PR outperforms FCFS. iPark (Zhao *et al.*) [153] benefited from the parked vehicles which have searched available parking places and then other vehicles can inherit the information in order to reduce parking time. Delot *et al.* [154–158] proposed a reservation protocol to allocate the parking spaces in a fully distributed environment. Each vehicle can release the available parking message to the network and look for a potential parker. If this vehicle gets a response, this parking place is reserved for it. Otherwise, a new coordinator shall be chosen in order to look for a potential parker in a farther area. PhonePark [67; 168; 169] used sensors on drivers' smartphone to detect their activities, e.g., accelerometer, bluetooth and GPS. The accelerometer can sense driver's movement to know if s/he is in the car, stationary or walking. Bluetooth pairing between vehicular on-board unit and smartphone can indicate if driver is in the car or not. GPS can provide driver's spatial and temporal information in order to charge the parking fee. Since a driver enter his/her car and is ready to leave, the parking place will be available for someone else. Thus, the car will advertise this information with other vehiculars and a vehicular network is then formed to share parking information according to the detected drivers' behaviours on their smartphones. Kokolaki *et al.* [159; 160] proposed an opportunistically assisted parking search (OAPS) in S2V and V2V communications. Some results are shown by comparing with the blind and centrally assisted ways. The central parking search can help drivers to find parking faster but OAPS can help drivers to find a closer parking place. Since the information dissemination is supported by drivers themselves, it is considered as a crowdsourcing dissemination network. Drivers can decide to distribute the information they received (forwarder), to falsify the information and distribute it (selfish liar), or do nothing (freerider) [94; 95].

2.4.2 Parking Competition

Dynamic pricing is currently the most efficient to regulate the parking occupancy status and traffic congestion. Unlike the dynamic pricing policy of SFpark, which changes the parking price on the average occupancy in a review period, Zoeter [31] took the deployment of LA ExpressPark and proposed a dynamic pricing policy with a Markov Chain model. The model can then predict the amount of parking demands and adjust the price before the car park is congested (occupancy rate > 90%) or underused (occupancy rate < 70%). Doulaïms *et al.* [191] improved the smart parking reservation policies by using maxima interval scheduling and dynamic pricing.

Dynamic pricing is often combined with multi-agent system, allowing to describe the behaviors of different individuals and interactions among them. Chou *et al.* [178] modeled the parking price negotiation in a multi-agent system. Each parking manager announces the parking places and waits for the bids from potential parkers. Thus, the parking price will change dynamically according to the intensity of competition. Dell'Orco *et al.* [179; 180] also proposed to match the parking demand and supply under dynamic parking pricing by using a multi-agent system. The drivers' perceived parking cost is described by a fuzzy set in order to present their imperfect knowledge on both parking and system status. Di Napoli *et al.* [184] adopted a software agent negotiation mechanism, which establishes an agreement between drivers and parking manager considering drivers' preferences, e.g., location and cost.

Fuzzy logic system can be used to describe drivers' decisions. PFLBS [187], namely parking finding location-based service, is developed based on a case study of the Oats Street and Carlisle PnR facilities in Perth, Western Australia. Fuzzy logic forecast models were used to estimate the uncertainty of parking availability during the peak parking demand period. Teodorović *et al.* [188] referred to the municipal parking projects, such as in San Francisco, Chicago, Seattle, and proposed a fuzzy logic system in order to know when to accept or reject a new parking request for the pricing policy.

Drivers might get a list of potential parking places and visit them one by one until they get one. Thus, the path between different parking places is quite important according to their locations and availability probability. Verroios *et al.* [64] targeted the traveling path planning while driving to parking places. Since street parking places have no barrier to keep available for reserved drivers, drivers have to visit the available places one by one until they can park. When drivers send their parking requests to roadside infrastructure, they get a list of available parking places with the probability of still-free. Each vehicle uses a clustering algorithm to classify the parking places and then plan the trip as a time-varying travelling salesman problem.

However, parking competition is interactive. If we try to look the entire system from bird's eye view, each driver is involved in a parking game and each decision might have a butterfly effect. Song *et al.* [173] modeled the parking search as a game and then analyzed if the municipal parking policy is suitable. Ayala *et al.* [174–177] focused on the parking competition. Each driver shall be assigned a parking place s/he prefers, or the parking assignment will not be stable, to wit, stable marriage problem. Authors modeled the parking decision by a gravity-based parking algorithm and a game theory model. That is each driver will calculate the gravity value of each parking place with respect to him/herself and his/her neighbors. If his/her gravity value is higher than others, s/he will take this parking place. Karaliopoulos *et al.* [181–183] analyzed the parking choice between on-street parking and car park. By assuming that each driver can know how many competitors he has for on-street parking, drivers might change their mind and provoke a chain reaction. A game-theoretical model is formulated for the drivers' decisions. Authors show the parking search efficiency between optimum, priority

heuristic and Nash equilibrium. CGPS [190] stands for collaborative game in parking lot search. Authors evaluated CGPS based on game theory in a distributed vehicular network. To collaborate, all vehicles received not only their own cost but also the extra cost of opponents. Based on this, Nash equilibrium is derived to raise the parking search efficiency. Sarasua *et al.* [189] presented a parking distribution way using the Hitchcock transportation algorithm. Since it considers the network cost, very realistic solutions were given and the system equilibrium could be achieved through optimal parking assignment combined with pre- and post-game traffic control strategies. Jin *et al.* [186] considers the fairness of parking space assignment. Since most drivers cannot arrive the assigned but too far parking spaces on time, the assignment scheme is not fair and shall take the real-time traffic information into account. The traditional First-Come-First-Served manner is not suitable to cope with the parking competition in rush hours. Authors propose an algorithm considering walking distance, driving direction and a time limit of arrival. Schlote [185] proposes a parking space assignment based on RED²⁵-like scheduling algorithm. Authors assume that vehicles only listen to broadcasts from car parks and then estimate the availability of a parking place based on the broadcast information. Authors extended the estimation model from single car park to several distributed car parks considering the effort of feedback on the choice of car park.

2.4.3 Driver's Parking Behavior

Parking behavior is an important criterion for smart parking system. Fig. 2.4 shows the different classifications while considering parking behaviors. The parking behavior is firstly concerned with parking system. H. Guo *et al.* [197] formulated the numerical models for through, parking and unparking vehicles and executed them in Monte-Carlo simulation. By changing the probabilities of (un)parking and vehicle arrival rates, the traffic and system capacity are also affected.

Continuing the parking game, each driver has his/her own preferences. PARKAGENT [195] an agent-based, spatially explicit model for parking in the city. It simulates the behavior of each driver in order to generate distributions of key values like search time, walking distance, and parking costs over different driver groups. It also shows that additional parking supply linearly affects the occurrence of extreme values, but has only a weak impact on the average search time for a parking place or the average walking distance between the parking place and the destination. Jossé *et al.* [196] worked on the search algorithm while coping with parking queries. Authors generated 100 test cases on real world street map data in Munich containing 40186 nodes and 96047 links. The authors compared the greedy and brute-force search algorithms. Greedy search algorithm outperforms on runtime under all conditions and on accumulated vacancy probability when there are more than 20 parking spots. Glasnapp [202] defines an intercept and online surveys in the context of LA Express Park. The results show an ethnographic study and if drivers are aware of dynamic pricing policy and mobile apps.

²⁵RED: random early dection, a scheduling algorithm which accepts all the requests when the buffer is almost empty. But if the buffer grows, the probability of dropping an incoming packet increases as well.

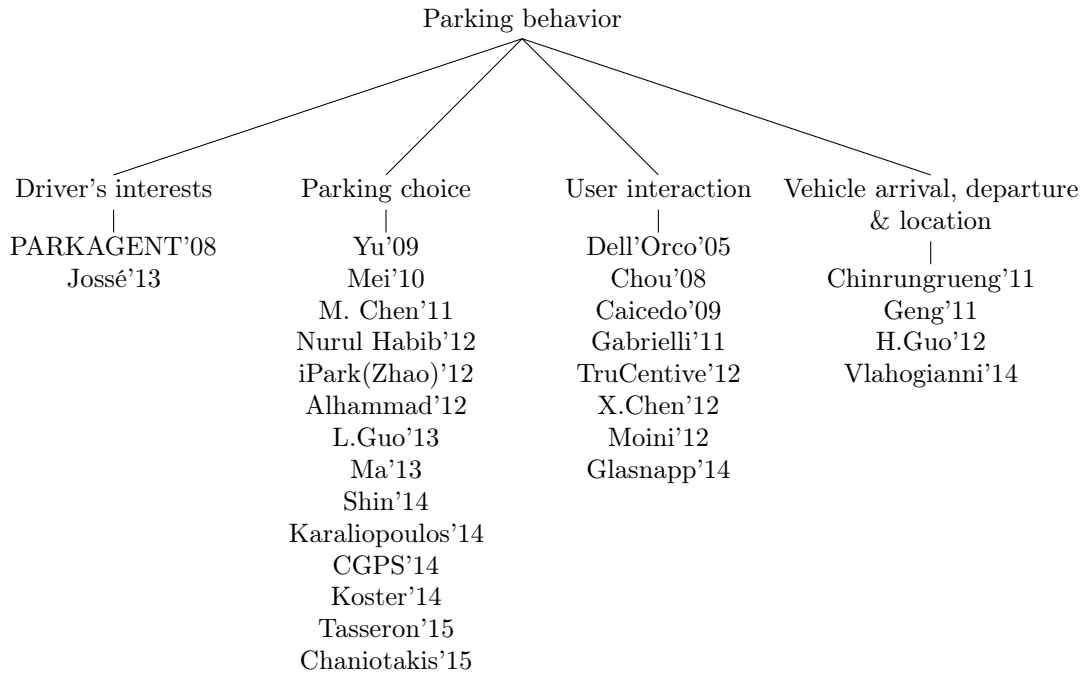


Figure 2.4: The diagram of parking behavior classification according to different focuses of drivers' behaviors.

Depending drivers' preferences, they might choose a parking place or not. If not, they will repeat parking search until they get one or they give it up. M. Chen *et al.* [200] firstly introduced the key factors influencing parking space choice and evaluated drivers' micro-behaviors in parking lots. Then, authors modelled an optimal parking space choices according to fuzzy multiple attribute decision making. Mei *et al.* [192] described a parking choice behavioral model incorporating drivers perceptions of waiting times at car parks based on VMS near Shanghai. Then the arrival rates were estimated based on driver characteristics, car park attributes and availability information. By using a genetic algorithm, queue length and total travel time are reduced. Caicedo *et al.* [193] introduced a PARK (parking access and revenue control) system and tried to change the information for drivers, in VMS, to see how drivers change their decisions and if drivers' search time reduced. Authors also proposed a methodology for predicting real-time parking space availability [194]. L. Guo *et al.* [198] proposed two kinds of parking choice models: a static game-theoretic model and a dynamic neo-additive capacity one in order to capture the competition between drivers for limited parking spaces. The static game assumes that drivers make decisions simultaneously with perfect knowledge about the characteristics of the parking system. The dynamic model considers individual drivers psychological characteristics under uncertainty, i.e., optimistic and pessimistic attitudes, and captures the impacts of the irrational side of parking behavior in addition to the rational aspect. The results show that the dynamic neo-additive capacity model has higher predictive accuracy to the parking system. Ma *et al.* [199] used six parking facilities in Beijing Lama Temple to investigate the parking behavior around the tourist site.

Authors developed a multinomial logistic regression model which reveals the relationship between parking decision and influential factors. Nurul Habib *et al.* [201] used a sample data set collected in Montreal, Canada. Since travel demand modelling has been undergoing a paradigm shift from the traditional trip-based approach to an activity-based approach, authors gave strong evidence that parking type choice influences the activity scheduling process. Yu *et al.* [204] focused on drivers' parking choice behavior while choosing an on-street or off-street parking place. Authors studied two groups of survey data. The first group was collected from drivers with complete parking information, and the second one from drivers with incomplete parking information. The results showed that compared with completely-informed drivers, incompletely-informed drivers prefer to pay less attention on walking time and safety but more on parking fee and some other factors. Chaniotakis [203] made a survey to see how drivers choose their parking places according to the probability of having it. A higher availability of parking after 8 minutes of search time is more important than a lower parking availability upon arrival. Four essential factors in determining parking place decision are parking costs, uncertain parking availabilities (availability after 8 minutes), walking distance to destination, and parking availability upon arrival in the order of importance.

2.5 Outlook

The results presented in the previous sections are many and diversified, covering different disciplines and topics. We see that the importance of working on smart parking solutions and it provokes many open questions. Our comprehensive survey puts us in a particular position to conclude the existing works and to provide some open questions. In this section, we give a summary and discussion along the line of our classification: information collection, system deployment and service dissemination.

2.5.1 Information collection

2.5.1.1 Parking detection sensor

In Section 2.2.1, magnetometer and smartphone are obviously the most common parking detection sensors. Although there are some non-governmental smartphone apps to gather parking information from everywhere in the world, such as Parkopedia, Crowdsourcing (e.g., Apila) and parking auction (e.g., ParkingAuction and mobypark), their popularity and convenience are still very limited. Most municipal deployment projects embedded plenty of magnetometers on on-street parking places, and then gather parking availability information via wireless sensor network or cellular link. Fixed sensors can help the government to monitor and manage city's resource anytime. Smartphone app is common for commercial use thanks to the popularity of smartphone (deployment-free). The large-scale sensor deployment requires a big financial expense but the city's revenue from parking ticket seems to be able to compensate the expense and give a promising future extension for smart city.

2.5.1.2 Wireless sensor network

Sensors deployed in cities have to be managed through network. Thus, short-range and long-range communication techniques are both used in the municipal deployments in Section 2.3.2. Both of them emphasize the importance of sensor's lifetime and autonomy, and information delay. The long-range communication can benefit from the existing radio access network and gives a promptly connection when needed. But to be energy-efficient, the amount and the size of data transmission are very restricted. The future extension requires the mature technology of the future generation of mobile network, and also the packets often travels farther among many different central units and are all billed. Short-range communication allows some small-size deployment for local service. The data transmission is often unlimited and compatible with present wireless networks. Else, it gives interesting features to maintain local information and can be the preliminary framework of smart cities.

2.5.2 System deployment

2.5.2.1 Software system

Smart parking system is an essential part to deal with all the parking resources and requests between parking information, drivers and cities. A framework or architecture for the integration of different technologies is usually presented and then software packages are proposed for reservation, payment, anti-thief, prediction, smart parking app and even the system agility. Municipal projects are often led by big companies and often proposes a system with the similar visions from the trade-offs between business advantages and technical reliability. The software systems are varied according to different commercial solutions, however, the user interface and the way to present parking information is quite similar. A group of parking places is aggregated and simply gives a probability of availability to drivers.

2.5.2.2 Data Analysis

Since city owns the spatio-temporal information of parking places, to study the characteristics of data is essential to improve the system efficiency and parking policy. The first purpose is often to propose a vacancy prediction model from collected data so as to show drivers the simplified and understandable information. Besides, the information can be also applied in service dissemination while drivers are completing limited parking spaces. Parking is a problem related to land use, vehicular traffic, city's revenue and human flow. The statistics of parking data will be able to indicate key factors for urban development from technical, economical and environmental perspectives. Since there are few large-scale deployment, the data analysis is still not easily accessible. But we can still see the increasing needs on data science.

2.5.3 Service dissemination

2.5.3.1 Information dissemination

Information dissemination hesitates if the infrastructure is required for urban services. An infrastructure-based system usually relies on roadside infrastructure or cellular basestation to provide information from parking detection sensors. Otherwise, sensor needs to be able to communicate directly with drivers in order to tell their own status with more anticipated battery capacity in a infrastructure-free mode. Whether infrastructure-based or infrastructure-free, both of them can increase their transmission opportunities by vehicle-to-vehicle communications in multi-hop network. In this case, how to guide messages via geographical multicast is an important question for the emerging vehicular networks.

2.5.3.2 Parking competition

Large-scale deployment gives some real-world examples while integrating parking sensors with software system. However, most drivers still have problem on finding parking because all drivers who have the same information always chase the same parking place. Also, drivers often do not get the appropriate information, e.g., parking places not on their ways. Thus, the information dissemination shall reduce the traffic flow instead of making drivers cruising for parking. Parking competition is then addressed to understand how the drivers' decisions and decisions can affect the parking system performance. Most systems proposed drivers to make a reservation to avoid conflicts. Besides, dynamic pricing and game theory are currently the two most instinctive methods. To define the parking game, each driver's individual behavior is significant, e.g., vehicle's arrival and departure, user interaction with the parking system via smartphone or VMS, parking decision and drivers' interests. Vehicle's arrival and departure are often linked with markov chain model and combined with parking prediction from historical data.

In this thesis, I mainly focus on the smart parking service from the viewpoint of the city. That is, the information accuracy, timeliness and reliability shall be equally important. Two following parts are urban sensing and urban service in which we will explain our insight and solution for smart parking system deployment.

Part II

Urban Sensing: An Engineering Insight for Wireless Sensor Network

Network Architecture and Protocols

3.1 Introduction

As the urban population is increasing, it brings economic growth and denser urban mobility. Thanks to the smartphone technology, drivers can get diverse urban information simply from mobile apps. Thus, the availability and quality of urban information become one of the most important criteria for smart cities. User-generated urban information is the first proposed and enriches the information sources at different prospects. Various interesting information can also be shared according to users' sudden or periodic urban mobility. The published content could, however, be outdated or false because of insufficient participants or malicious users, as well as limited to human's observation. In view of this fact, wireless networked sensor devices help obtain more types of information and assure of the accurate measurement. According to information types, sensor devices send updated information periodically or on-demand. That is, a network packet which consists of certain information, shall be treated with its corresponding priority in order to respect an acceptable information delay. The increasing mobility motivates new urban services to be carried out by networked sensor devices. In particular, traffic congestion is one of the major issues of metropolis and a huge percent of traffic jams are caused by vehicles looking for parking spaces. So far as urban drivers are concerned, smart streetside parking system assisted by networked sensor devices is needed to shorten the parking search time and the parking distance to destinations.

These networked parking sensor devices detect the availability of parking spaces and form a wireless sensor network (WSN). Such a so-called parking sensor network (PSN) has the following characteristics.

- Parking sensors are stationary, in-ground and scattered with a minimum adjacent distance.
- The network topology is linear and limited by the urban street layout.
- The sensing areas of the parking sensors do not intersect to avoid multiple detection.
- Packet generation rate depends on the vehicle's arrival and departure.
- The availability of parking places should be delivered as a real-time service.

Based on these, we see the importance of device lifetime considering their maintenance and latency while providing real-time service to urban citizens. PSN is a specialized

form of WSN and inherits its energy and delay constraints. To optimize network parameters for best performance, the network traffic is significant. Three mainstream traffic models are request, event and time-driven. Request-driven models are irrelevant for parking sensor networks since continuous recording is required for municipalities. Time-driven or periodic application is often used in testing the performance of network protocols because of its low dependence to the environment. Event-driven application is tricky due to its variety on different types of observed events.

Considering different configurations of parking sensor networks, the MAC protocol, which deals with the bandwidth allocation, will be the first to be confronted. The WSN MAC protocols are mainly classified as contention-based and schedule-based. Contention-based protocols, such as CSMA/CA, are widely used for sensor nodes. Schedule-based, also known as contention-free, protocols require at least one central node time-synchronized or asynchronous networks. Asynchronous methods need to perform a low power listening (LPL) before transmitting each packet, thus its cumulative energy dissipation is not favorable for parking sensor network. From our survey, we focus on the impact of traffic intensity on time-synchronized MAC protocols. Our body of work is to simulate the traffic influence on stationary WSN with the aim of improving the design of network architecture.

Our contributions are summarized as follows: First, we model the periodic and event-driven urban parking sensor applications by observing vehicle's arrival and departure. Second, we evaluate the energy and delay performance of two different applications through extensive simulations on urban scenarios, so as to compare two fundamental MAC protocols. Third, we provide some key thresholds which help to find a best configuration, and highlight the importance to develop an adaptive MAC protocol which can detect the traffic intensity and switch between different configurations when required. Fourth, we also highlight some remarkable issues for deploying multihop parking PSN.

3.2 Related works

Smart on-street parking's main mission are to collect the real-time parking availability information and to disseminate the information to mobile users through a smart-parking app. Two types of collection methods are mobile and stationary. The former is to take advantage of vehicle's mobility to collect information along the route. In which, the most economical is crowdsourcing based mobile application. It is obvious that crowdsourcing parking assistance system cannot provide a reliable real-time service required by municipalities [205]. Neither does the mobile sensor side-mounted on a taxicab or bus for detecting an on-street parking map. For example, the ParkNet system in San Francisco [11], collects data with the location information from GPS receiver and then transmit it over a cellular uplink to the central server. Such a mobile parking sensor system requires much less installation, yet needs a longer average inter-polling time, to wit, 25 minutes for 80% of the cells in busier downtown area with 300 cabs. Stationary collection method is to install on-site vehicle detection sensors, as described in Chapter 2,

to monitor the occupancy status of parking spaces. Based on this, large-scale road-side parking sensor network has been implemented in many cities, e.g., SFPARK project [1] in San Francisco, LA EXPRESS PARK [24] in Los Angeles, FASTPRK in Barcelona, CONNECTED BOULEVARD in Nice and so forth. Among them, the efficiency of parking sensor network is the first concern. A lot of protocols have been proposed for urban WSN applications. We sort them out as the following three groups.

- CONTENTION-BASED protocols are much widely studied in WSN and generally based on or similar to CSMA/CA. When one node has a packet to send, it will have to struggle with the other competitors to get permitted of using the medium. The winner selection is somehow randomized. The synchronous MAC protocols are generally duty-cycled and require time-synchronized, such as S-MAC, T-MAC, CONTI [206], SIFT [207] and so forth. The state-of-the-art synchronization method is to be done through hardware or message exchange, and then a piggybacked acknowledge can be used to solve the clock shifting effect [208]. The asynchronous versions use *low-power listening* (LPL) or its preamble-shortened approach to match up the transmission period between transmitter and receiver end, such as B-MAC, WISEMAC, X-MAC, SCP-MAC [209], RI-MAC [210] and so on. Among them, [211–213] compared the power dissipation between asynchronous and synchronous contention-based protocol. In which, LPL method is interesting in very low traffic intensity (less than one packet per day) or dynamically changing topologies. Otherwise, synchronous protocol outperforms asynchronous one. The drawback of such protocols is the packet collision caused by increasing network density and hidden terminal.
- SCHEDULE-BASED protocols are generally centralized and suitable for static topologies. Assigned nodes play the master role to allocate slotted network resource to their slaves. The mechanism is generally based on TDMA or CDMA. The clock of each node must be time-synchronized. Scheduled slots can be fixed or on-demand. Some noted protocols are like DRAND [214], LEACH [215], TRAMA [216] and TSMP [144]. They use TDMA as the baseline MAC scheme, and then take CSMA, ALOHA or CDMA for improving their join/leave/synchronize messages. The main drawback is the difficulty to adapt to the dynamics of network. In particular, the signaling volume and time to get a response of the centralized control adapting the schedule to the traffic variation.
- HYBRID CONTENTION-BASED & SCHEDULE-BASED is to combine the advantages of both protocols in order to reach the best performance. Z-MAC [217] behaves like CSMA under low competition and under high competition, like TDMA. FUNNELING-MAC [218] uses CSMA as the baseline, and changes to TDMA while receiving on-demand beaconing from the sink, that is to say, nodes close to the sink performs TDMA. FUNNELING-MAC works in the application of data collection. IQUEUE-MAC [219] runs in CSMA in light load and then uses queue-length piggybacking as accurate load information to ask for additional variable TDMA time slots if needed.

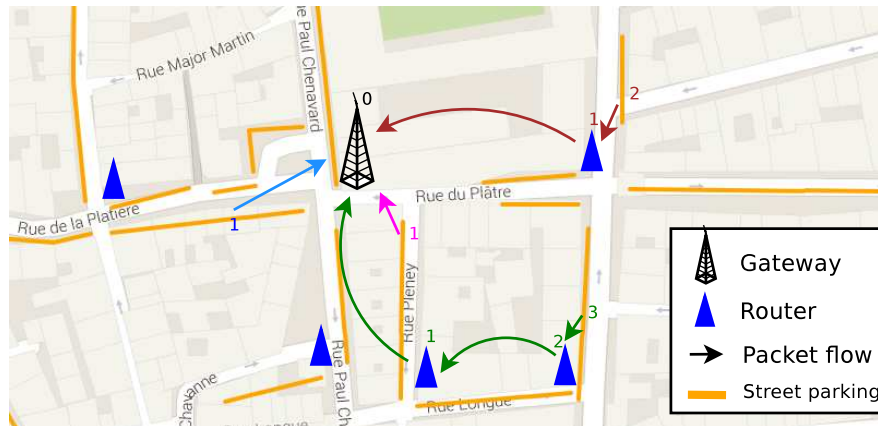


Figure 3.1: Multihop parking sensor network

The occupancy and vacant durations are different to get due to the constraint of real PSN implementation. In the past literature, arrivals and departures were generally assumed Poisson distributed, and the occupancy rate of the parking system was analyzed by Markov processes. However, the report of SmartSantander has shown that the vehicle's occupied time can be described by a Weibull distribution [135]. Therefore, which type of MAC protocol suites best the urban smart parking application in terms of network density and traffic intensity? In this chapter, we simulate several different scenarios with different network density, traffic intensity and two mainstream MAC protocols and their hybrid versions in order to find the best configuration while constructing urban WSN applications.

3.3 Multihop mesh network

3.3.1 Urban sensor topology

The topology of urban sensors is strongly related to the sensor type and city map. In PSN, sensors are installed on parking places. From the real implementation in SFpark project [1], the network deployment is quite consistent. All the wireless parking sensors are in-ground and have limited communication among themselves because of the soil medium [220] and vehicular obstacles. Thus, sensors regarded as RFD (reduced function device) can only communicate with routers or gateways which are FFD (full function device) and generally mounted on the streetlights or traffic lamps in crossroads. We illustrate an example of topology that could be deployed in a quarter of Lyon in Fig. 3.1. Packets generated on parking sensors have to travel from the closest routers hop by hop until they reach the gateway. The typical topologies of parking sensor networks can be categorized into three groups:

- **CROSSROAD:** Most routers or gateways are installed crossroads in order to reach their maximum coverage, i.e., each router or gateway can manage more sensors while installing in crossroads.

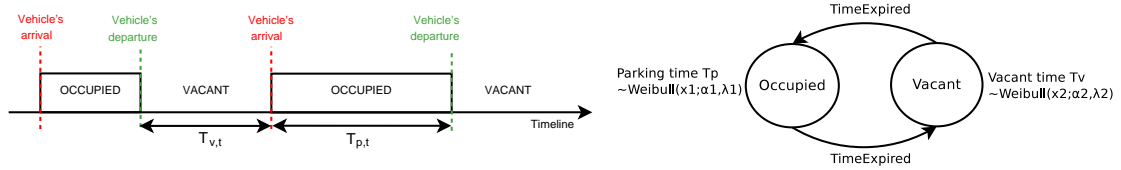


Figure 3.2: (Left) Timeline of sensor's occupancy status. (Right) Sensor state transition diagram.

- LINE: For some long road segments, routers might be needed to guarantee sensors' connectivity.
- MESH: When enlarging the deployment scale, the network will be constituted of many small crossroad and line-type topologies. Thus, a mesh network between routers and gateway will be formed.

3.3.2 Routing protocol

In a multihop mesh network, the impact of a routing protocol on the performance is important. In our situation in which fixed sensor network gathers their packets in gateways, Gradient [221] routing is currently the most energy-efficient routing protocol. To start the routing discovery, the gateway sends a hello message to the network with an height value 0, sequence number, gateway address, and the last sender address. Each device, who received this hello message, increases the height value by one and then store it to their own cost table. If the lifetime of this message is not expired yet, it will be forwarded again to the Internet. Each device might receive several hello message, however, it will choose who has the smallest height value (closest path) to send its packets if needed. Gradient routing guarantees a single-direction route discovery from gateway and it conserves a half of control messages. Numbers in Fig. 3.1 stand for the height value of each device in a packet flow by using the gradient routing.

3.4 Parking intensity model

In urban sensor network, sensors are often stationary to monitor certain events, and hence the packet transmission shall always happen and never end. In other words, the key point of modeling an event-driven application will be to find an appropriate distribution to define the traffic interval, namely inter-event interval. Next, we present the modeling of the event occurrence and the definition of information delay with respect to urban smart parking applications.

3.4.1 Vehicle's arrival and departure

In PSNs, the main observed event are vehicles' arrivals and departures. For any parking sensor, each vehicle arrival accompanies exact by one departure prior to next arrival. To model it, we first look at the event occurrence sequence on one parking sensor. We suppose that each parking sensor is precise enough and provides merely two states, namely occupied and vacant, as shown in Fig. 3.2. The occupied time from vehicle's

arrival to departure is so-called parking time $T_{p,t}$, conversely, the vacant time is available time $T_{v,t}$. During which, each sensor detects the vehicle's presence or absence. Both $T_{p,t}$ and $T_{v,t}$ shall be described by a fitting distribution in order to approximate their randomness. From Vlahogianni's report [135], the massive real-time parking availability data, obtained by four on-street PSNs in Santander, shows that the occupied duration is best described by a Weibull distribution. Besides, the findings in [135] show that the duration of free parking space follows a Weibull distribution as well. By assuming that $T_{p,t}$ and $T_{v,t}$ are both Weibull distributed, the PDF of $T_{p,t}$ and $T_{v,t}$ is given by:

- $f_{X_1}(x_1) = \frac{\alpha_1}{\lambda_1^{\alpha_1}} x_1^{\alpha_1-1} e^{-(\frac{x_1}{\lambda_1})^{\alpha_1}}$ stands for the probability of choosing a parking time X_1 .
- $f_{X_2}(x_2) = \frac{\alpha_2}{\lambda_2^{\alpha_2}} x_2^{\alpha_2-1} e^{-(\frac{x_2}{\lambda_2})^{\alpha_2}}$ stands for the probability of choosing a vacant time X_2 .

where $0 < \alpha_i < 1$ is a shape parameter and λ_i is a scale parameter, for $i = 1, 2$. Let X be the sum of two i.i.d. Weibull variates X_i , i.e., $X = X_1 + X_2$. The approximate PDF and CDF of X proposed in [222] are given by:

$$f_X(x) = \frac{\alpha}{(\lambda^\alpha)^\mu} \frac{\mu^\mu}{\Gamma(\mu)} x^{\alpha\mu-1} e^{-\mu(\frac{x}{\lambda})^\alpha} \quad (3.1)$$

$$F_X(x) = 1 - \frac{\Gamma(\mu, \mu(\frac{x}{\lambda})^\alpha)}{\Gamma(\mu)} \quad (3.2)$$

where α is a shape parameter, λ is a scale parameter such that $E[X^\alpha] = \lambda^\alpha$ and $\mu = E^2[X^\alpha]/Var(X^\alpha) > 0$. $\Gamma(\cdot)$ is the gamma function and $\Gamma(\cdot, \cdot)$ the incomplete gamma function. If we take $\alpha_1 = 0.4$, $\lambda_1 = 3600(s)$, $\alpha_2 = 0.7$ and $\lambda_2 = 900(s)$ referring to [135], and then the vehicle interarrival time of one parking place is obtained as $T_p + T_v = X_1 + X_2 = X$ in Figure 3.3. From the survival function of vehicle interarrival time, we see that X is also heavy-tailed, i.e., $0 < \alpha < 1$. α , μ and λ can be obtained by equations (3.3)–(3.5) written in [222].

$$\frac{\Gamma^2(\mu + \frac{1}{\alpha})}{\Gamma(\mu)\Gamma(\mu + \frac{2}{\alpha}) - \Gamma^2(\mu + \frac{2}{\alpha})} = \frac{E^2[R]}{E[R^2] - E^2[R]} \quad (3.3)$$

$$\frac{\Gamma^2(\mu + \frac{2}{\alpha})}{\Gamma(\mu)\Gamma(\mu + \frac{4}{\alpha}) - \Gamma^2(\mu + \frac{2}{\alpha})} = \frac{E^2[R^2]}{E[R^4] - E^2[R^2]} \quad (3.4)$$

$$\lambda = \frac{\mu^{\frac{1}{\alpha}} \Gamma(\mu) E[R]}{\Gamma(\mu + \frac{1}{\alpha})} \quad (3.5)$$

where $E[X^n]$ is the n^{th} moment of X and given by $E[X^n] = \sum_{n_1=0}^n \sum_{n_2=0}^{n_1} \binom{n}{n_1} \binom{n_1}{n_2} E[X_1^{n-n_1}] E[X_2^{n_1-n_2}]$. X_i is Weibull distributed so that its n^{th} moment is $E[X_i^n] = \lambda_i^n \Gamma(1 + \frac{n}{\alpha_i})$. The count model based on Weibull interarrival times is studied in [223]. The probability of k arriving vehicles in a given interval is given as below:

$$P(N(t) = k) = \sum_{j=k}^{\infty} \frac{(-1)^{j+k} \left(\frac{t}{\lambda}\right)^{\alpha j} \Delta_j^k}{\Gamma(\alpha j + 1)} \quad k = 0, 1, \dots \quad (3.6)$$

where $\Delta_j^{k+1} = \sum_{m=k}^{j-1} \Delta_m^k \frac{\Gamma(\alpha j - \alpha m + 1)}{\Gamma(j - m + 1)}$ for $k = 0, 1, 2, \dots$ and $j = k + 1, k + 2, k + 3, \dots$. $\Delta_j^0 = \frac{\Gamma(\alpha j + 1)}{\Gamma(j + 1)}$ $j = 0, 1, 2, \dots$. In a business area or on weekdays, the average free time can be shorter according to the area hourly activities or parking policy. Its impact on the network traffic will have to be considered as well. The vehicle's interarrival duration can be expressed as $Z = T_{p,t} + T_{v,t}$ in which, one turnover is counted. The occupancy rate will be $E[T_{p,t}/(T_{p,t} + T_{v,t})] = \lambda_1 \Gamma(1 + \frac{1}{\alpha_1}) / (\lambda_1 \Gamma(1 + \frac{1}{\alpha_1}) + \lambda_2 \Gamma(1 + \frac{1}{\alpha_2}))$. From literature, Pareto and Weibull distribution have been discussed to describe the burstiness of network traffic. While looking at the Figure 5 in [135], the occupancy duration in four different regions follow the Weibull distribution with the shape parameters approximately 0.4~0.7. When the shape parameter is smaller than 1, the occupancy duration is heavy-tailed [224]. We took the Weibull parameters in [135] and then get its CDF and survival of Z in Fig. 3.4. Hence, if $T_{p,t}$ and $T_{v,t}$ are both heavy-tailed, so is $T_{p,t} + T_{v,t}$. From [225], the CDF $F(t)$ of interarrival time Z has regularly varying tail such that: $1 - F(t) \sim t^{-\varepsilon} L(t)$ as $t \rightarrow \infty$. $L(t)$ is a slowly varying function at infinity, that is, $\lim_{t \rightarrow \infty} L(tx)/L(t) = 1 \quad \forall x > 0$. From Mitov's model, the distribution function of the interarrival times is Weibull with $0 < \varepsilon \leq 1$, the shape parameter $\nu = 1 - \varepsilon$ and scale parameter $\gamma = C \sin \frac{\pi \varepsilon}{\pi(1-\varepsilon)}$, provided that $Nt^{1-\varepsilon} \rightarrow C$, $0 < C < \infty$ and N is the number of traffic sources, the parking sensors in our case. If we increase the amount of observed parking places, i.e., N , the vehicle interarrival time is shown in Fig. 3.5 and the shape parameter is approximately 1.

3.4.2 Event-Driven versus Periodic

3.4.2.1 Event-driven traffic

If each parking sensor sends a packet when its sensing state changes, the packet interarrival time Y is confined to the vehicle's interarrival time and will be also heavy-tailed with the shape and scale parameters A and Λ , where $A = \alpha$ and $\Lambda = 0.294\lambda$ in Fig. 3.3. Next, we look at a group of parking sensors and evaluate the vehicle interarrival time for a parking area. Here, the vehicle interarrival time stands for the interval of any two consecutive vehicle arrivals of different parking spaces in this area. When the network size increases, the vehicle interarrival time tends to an exponential distribution, shown in Fig. 3.4, i.e., $\alpha \rightarrow 1$. In which, the relationship between vehicle and packet interarrival time varies from $\Lambda = 0.25\lambda$ (2 sensors) to 0.225λ (24 sensors). Fig. 3.5 shows that the packet and vehicle interarrival times of a 24-parking-sensor network follow an exponential distribution (the Weibull's shape parameter is equal to 1). The average interarrival of network packets from parking sensor i is $\frac{1}{2}(\lambda_{1,i} \Gamma(1 + \frac{1}{\alpha_{1,i}}) + \lambda_{2,i} \Gamma(1 + \frac{1}{\alpha_{2,i}}))$ per second. While considering N parking spaces, the count model of total generated network packets is:

$$C_N(\Delta t) = \sum_{i=1}^N \frac{2\Delta t}{\lambda_{1,i} \Gamma(1 + \frac{1}{\alpha_{1,i}}) + \lambda_{2,i} \Gamma(1 + \frac{1}{\alpha_{2,i}})} \quad (3.7)$$

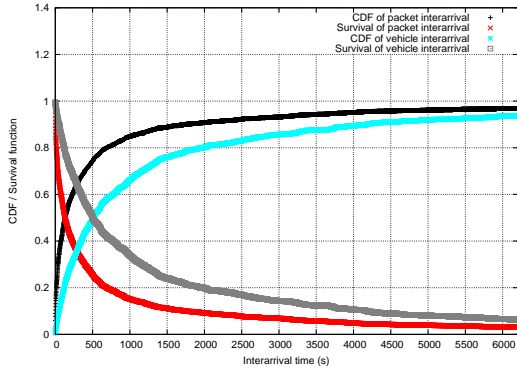


Figure 3.3: The CDF and survival function of vehicle and packet interarrival times of one in-ground parking sensor

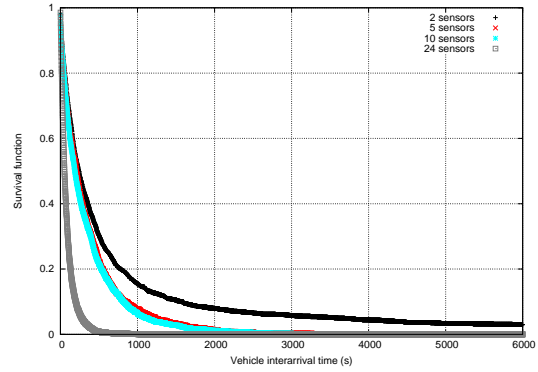


Figure 3.4: The survival function of vehicle interarrival times of 2, 5, 10 and 24 in-ground parking sensors

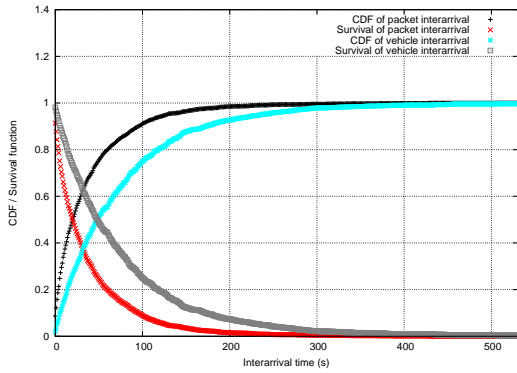


Figure 3.5: The CDF and survival function of vehicle and packet interarrival times of 24 in-ground parking sensors

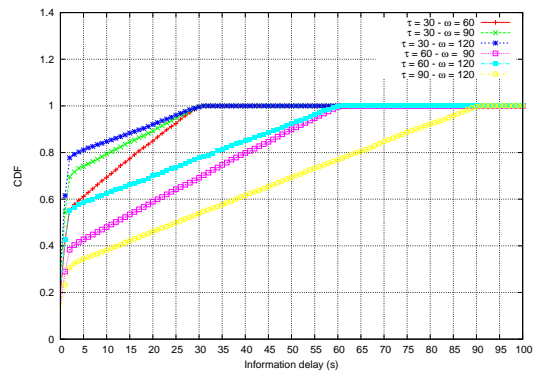


Figure 3.6: Periodic and Event-driven mixed application with different τ and ω combinations.

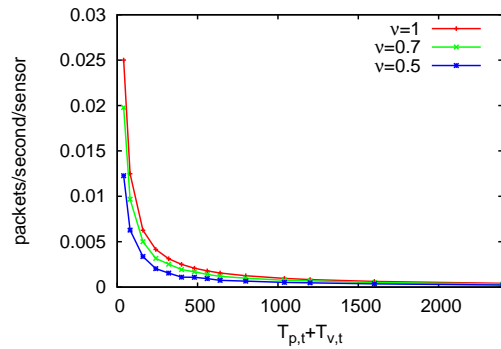


Figure 3.7: Generated packets by event-driven traffic model while all sensors have the same mean of interarrival time($\frac{\lambda}{2}$) but different shape parameters(0.5 and 1).

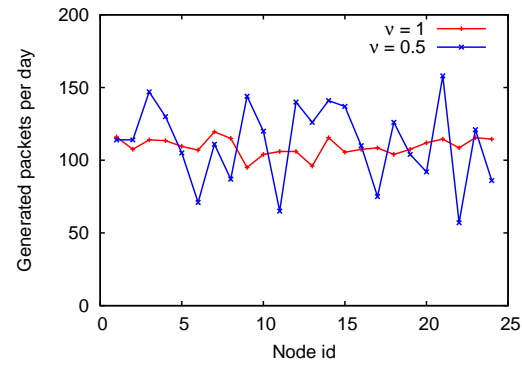


Figure 3.8: Traffic difference between sensor nodes while all the sensors have the same mean of interarrival time($\frac{\lambda}{2}$) but different shape parameters(0.5 and 1).

Where Δt is the observation period. When $C_{N_1}(\Delta t) = C_{N_2}(\Delta t)$, the packet and vehicle interarrival durations are the same. However, in such a case, even though $N_1 = N_2$,

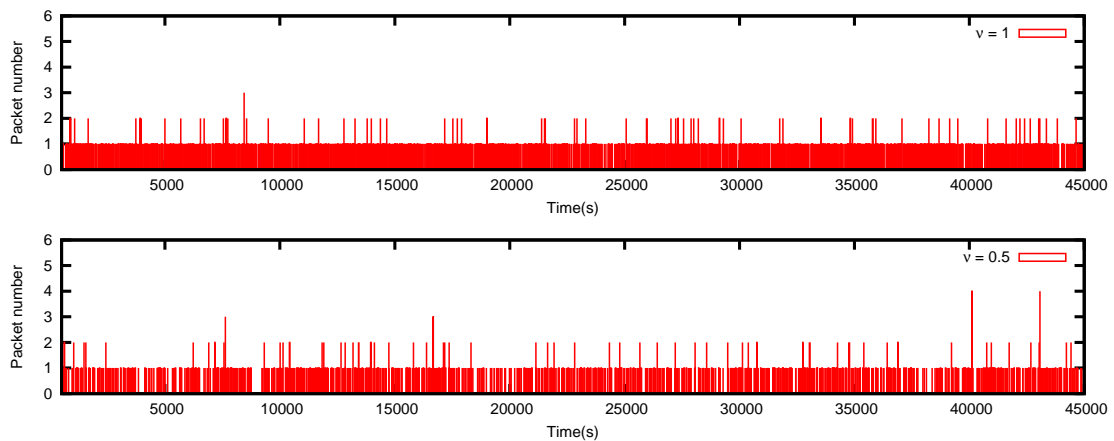


Figure 3.9: Timeline of Network Traffic when having the same scale parameter but different shape parameters 0.5 and 1

we can still find several sets of different combinations of λ_1 , α_1 , λ_2 and α_2 . These parameters decide the variation of $T_{p,t}$ and $T_{v,t}$ which give the information about the utilisation of street parking.

Exponential distribution has been widely used for simulating the vehicle's arrival. It is a Weibull distribution with shape parameter equals to 1. Next, we try to compare the performances while applying Weibull distribution in the network traffic model with respect to Exponential distribution. Fig. 3.7 shows that the packet generation rate is strongly decided by the sum of $T_{p,t}$ and $T_{v,t}$ from equation (3.7), and also proportional to the shape parameter(A) when the scale parameter(Λ) is fixed. The reason of reducing packet generation rate is caused by part of longer parking occupancy time, which is well described by heavy-tailed distribution.

Then we fix the average of vehicle interarrival time and compare two different shape parameters 0.5 and 1. In Fig. 3.8, we see that the non-uniform property is more obvious when the shape parameter is smaller than 1. This is because the infinite mean and infinite variance which make a larger variation among parking sensors. Moreover, what is the impact to the gateway, namely network coordinator? Fig. 3.9 shows the network load while managing 24 parking sensors. We can see clearly that when the shape parameter is 0.5, the burstiness of network traffic is more significant and cannot be considered as an Exponential distribution.

3.4.2.2 Periodic/Time-driven traffic

On the contrary, periodic application is only affected by the traffic interval ω instead of event occurrence frequency. The amount of generated packets is inversely proportional to the traffic interval. While using periodic traffic model, the amount of network traffic is unaffected by the sensory information. It simply sends out a packet with the current time-stamped status when the time is up.

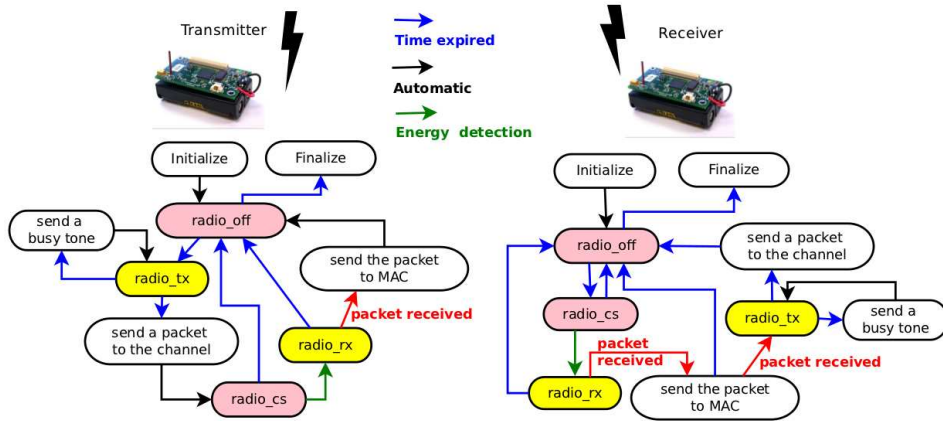


Figure 3.10: Radio behavior of sensor device

3.4.2.3 Hybrid periodic and event-driven traffic

By assuming that the sensory information is small enough to merge into the packet with energy status information, we define a time parameter τ as the threshold to decide when the information is going to be sent. When the sensing state changes at the time point t_{now} , it will check the delivery time of next periodic packet t_{next} . If $|t_{now} - t_{next}| < \tau$, the occupancy information will be put into the periodic packet to reduce the transmission frequency. Otherwise, this information will be canned into a packet and sent immediately. This way, all the parking information shall be delivered within τ seconds. In PSNs, we evaluate the information delay to estimate if the protocol is efficient enough. Information delay is the required time to know a changed occupancy status of a parking sensor. Figure 3.6 shows the CDF of information delay while applying hybrid periodic and event-driven application. For the generated information such that $|t_{now} - t_{next}| < \tau$, the packets will be sent within τ seconds uniformly. Otherwise, the packets will be sent right now and will arrive at the destination in 1st duty cycle (T_{cycle}) since the network traffic is not that heavy. The probability of packet arriving in 1st duty cycle is given as $Pr\{I_i | t_{next} - t_{now}(I_i) \geq \tau\} = \frac{\omega - \tau}{\omega} + \frac{T_{cycle}}{\omega}$, and the probability of packet arriving between 1st duty cycle and τ is $Pr\{I_i | t_{next} - t_{now}(I_i) < \tau\} = \frac{\tau - T_{cycle}}{\omega}$, where I_i is the i^{th} sensed information. Hence, the smaller $\frac{\tau}{\omega}$ is, the shorter information delay we expect.

3.5 Bandwidth allocation

3.5.1 Radio and energy models

3.5.1.1 Energy models of different sensor boards from different providers

For maximizing the sensor's lifetime, each device applies a duty-cycled bandwidth allocation. That is, when devices have packets to send or receive, it simply turns its radio on. Otherwise, the radio shall be off. To implement this, four different radio states emerge to meet the requirement in Fig. 3.10: transmission (radio_tx), reception (radio_rx), carrier sensing (radio_cs) and radio off (radio_off). The total energy consumption of a device shall be:

$$\begin{aligned}
E_{total} &= E_{tx} + E_{rx} + E_{cs} + E_{off} + E_{radio.switch} \\
&= P_{tx} \cdot T_{tx} + P_{rx} \cdot T_{rx} + P_{cs} \cdot T_{cs} + P_{off} \cdot T_{off} + E_{radio.switch}
\end{aligned}$$

Where E and P stand for energy and power. P_{tx} , P_{rx} , P_{cs} and P_{off} are restricted by manufacturers. T_{tx} and T_{rx} are determined by data rate of radio. Thus, to maximize T_{off} , the only way is to minimize T_{cs} . We will introduce how the scheduling is made in order to reduce T_{cs} period.

3.5.2 MAC layer scheduling

Considering that WSN is often bandwidth-limited, the only medium resource is time divisions in a single-channel scenario. From literature, we found that choosing a MAC protocol has been the subject of much controversy in urban sensor networks. We have selected four different types of MAC protocols in order to evaluate the network performance. They are contention-based, schedule-based and hybrid from both of them respectively. From the reason mentioned in Section 3.2, these MAC protocols are all duty-cycled, time-slotted and run in a time-synchronized environment. To minimize the idle listening period in each data slot, each transmitter sends a very small beacon to reserve the medium before starting the data transmission. If the reservation fails, the transmitter will put back the packet into its queue, turn off its radio and wait for the next time slot. Instead of wasting energy to do a vain transmission, sensor nodes prefer to evaluate the receiver's availability through these very small beacons. Our work is to find the most appropriate MAC protocol to deal with the data transmission in the CAP (contention access period) of IEEE 802.15.4 MAC standard [226]. For a better comparison in CAP, these four MAC protocols apply the same amount of time slots and the hybrid versions will adjust the percentage of TDMA or CSMA slots in order to combine the advantages of TDMA and CSMA in one protocol. $T_{cycle} = (n_{csma} + n_{tdma}) * s_D + T_{GTS} + T_{inactive}$ for n is the slot number.

3.5.2.1 Contention-based bandwidth allocation

CSMA is the default version of CAP in the MAC layer of IEEE 802.15.4. CSMA is the typical contention-based protocol and widely applied in practice. The principle is that the node gets its part of the network resource when it asks for. If more than two nodes declare their demands simultaneously, a competition will happen to decide who is the actual transmitter. Each candidate transmitter chooses a backoff time, after which it sends a reservation beacon. While waiting it listens to the medium. If it hears any beacon in the meantime, it will turn off the radio and wait for the next time slot. The advantages of contention-based resource allocation are the better use of network resource and a short network delay. The drawbacks is the inevitable packet collision which causes arbitrarily high energy consumption and latency on grounds of endless competitions triggered by high node density. If there is a new node which intends to join this network, it will just join the competition and increase the packet collision rate.

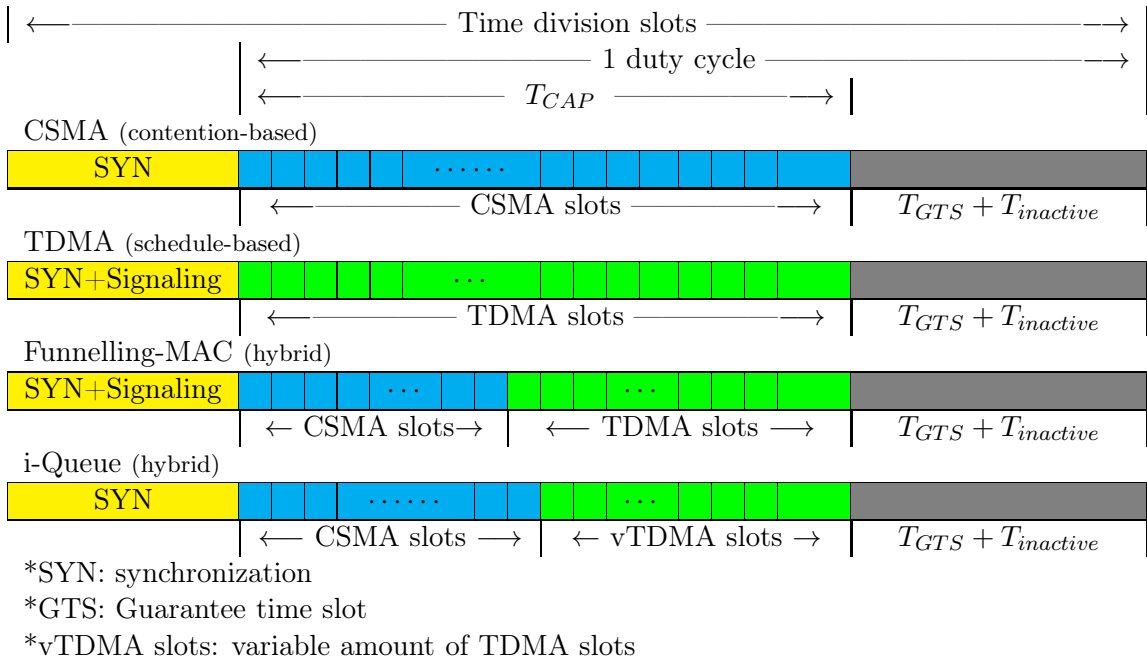


Figure 3.11: Slot allocation methods of CSMA, TDMA, Funnelling-MAC and i-Queue MAC protocols

3.5.2.2 Schedule-based bandwidth allocation

TDMA, the typical MAC protocol for schedule-based B.A., is based on a preassigned schedule managed by the network coordinator. Each node arrived in the network will send a request in order to be preassigned to one partition of medium resource to transmit their packets. While the network coordinator does not know in advance the traffic model and node position, it preallocates one partition to all the nodes in his subnet. If a node has no packet to send in its item, the other still cannot seize this occasion to send their packets out. TDMA can achieve a very little packet collision rate but is inflexible for its central schedule control. A signaling process is always needed when the network topology changes. The advantages of schedule-based B.A. are the nearly very little packet collision rate and lower energy consumption since nodes only send beacons in certain slots. If sensor nodes' traffic model is given, schedule-based B.A. can optimize the resource assignment to reach a better performance. The drawbacks are that many time slots are wasted and a longer delay time is caused, also the urban traffic model is dynamic and time-variant. Moreover, if there is a new node which intends to join this network, the gateway will have to reallocate the resource while there is no enough time slots.

3.5.2.3 Hybrid contention and schedule-based allocations

We choose two adaptive hybrid MAC protocols, Funnelling-MAC and i-Queue, in order to find a balance between contention and schedule-based methods. Fig. 3.11 explains the differences between CSMA, TDMA, Funnelling-MAC and i-Queue.

Simulation time	86400 seconds
Batch experiences	#20
Sensor number	12 ~ 120
Gateway number	1
Distance	Between two adjacent sensors: 5 meters
	From the gateway to its vicinal sensors: 10 meters
Transmit power output	3 dBm
Receive sensitivity	-85 dBm
Radio	802.15.4 with data rate 250 kbps
Power	$P_{tx}=65.7\text{mW}$, $P_{rx}=56.5\text{mW}$, $P_{cs}=55.8\text{mW}$, $P_{off}=30\mu\text{W}$
	$E_{radio.switch}=0.16425\text{mJ}$
MAC	Duty-cycled schedule & contention-based bandwidth allocation
	Slot duration(s_D)=0.1s. Retransmission & Piggyback
Application (scenario 1 & 3)	Event-driven - λ_1, λ_2 & $\alpha_1 = \alpha_2 = 0.5$, Periodic - ω
	Packet size 84 bytes
Application (scenario 2)	T_p parking time \sim Weibull($x_1; \alpha_1, \lambda_1$). $\alpha_1 = 0.4$. $\lambda_1 = 60 * 60$.
	T_v vacant time \sim Weibull($x_2; \alpha_2, \lambda_2$). $\alpha_2 = 0.7$. $\lambda_2 = 15 * 60$.
	Packet size 84 bytes
	Hybrid event-driven and periodic: $\omega = 120s$. $\tau = 30s$
Routing	Gradient [221] with an update period of 8000 seconds
Propagation	Corner pathloss($\lambda = 0.125$) [227] + Rayleigh fading

Table 3.1: Simulation parameters for contention-, schedule-based, and hybrid bandwidth allocation methods

- Funnelling-MAC [218] is a hybrid version of TDMA and CSMA. All devices run CSMA by default. The devices, which are N -hop away from the gateway, will change to TDMA and then ask for a time slot to the gateway. When $N = 1$, Funnelling-MAC works nearly like TDMA in one-hop scenario. Funnelling-MAC is equal to TDMA when $N = \#$ Max Hop.
- i-Queue [219] sets a one-byte queue indicator in the MAC header, so that the gateway will be informed of the additional demands from data packets and reply with some additional time slots from vTDMA (variable TDMA) slots. If the gateway receives no request of vTDMA slots, the duration of vTDMA slot will become inactive and useless for sensor nodes. Since the packet interarrival time is scattered in PSNs, i-Queue MAC behaves nearly like CSMA. Here, we assume that only the gateway can issue an additional vTDMA slots to the nodes one-hop far away.

3.6 Evaluation

Our simulations, performed with the WSNET simulator [228], use the simulation parameters in Table 3.1. We first take one small cell in a crossroad with different network density for scenario 1. The topologies are depicted in Fig. 3.12. Then we configured 3 different topologies by referring to the three regions in [135] with traffic parameters for scenario 2. To clarify the influence of four different MAC protocols, we choose one set of parameters from them for scenario 2. The topologies are depicted in Fig. 3.22. Finally,

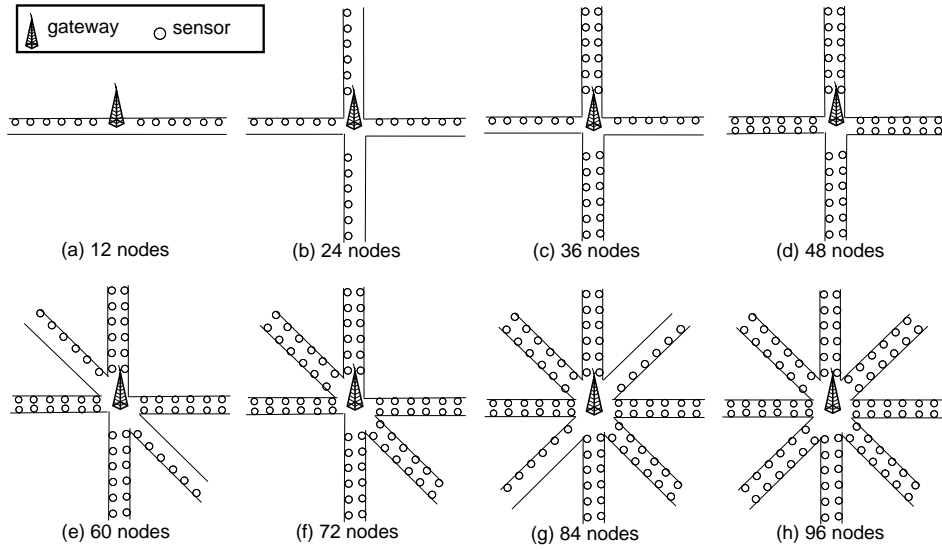


Figure 3.12: Topologies of different numbers of sensors. Increase the node density by adding one more line or one more side of curb parking.

we reuse the R3 to produce the scenario 3 in order to see the impact of transmission power. We set the slot durations are both 0.1 seconds in order to have the same active time and so does the throughput.

3.6.1 Impact of traffic intensity and node density - scenario 1

3.6.1.1 Impact of network density

Figures 3.13 and 3.14 shows the per-node energy consumption using periodic and event-driven network traffic models. The x-axis stands for the sensor number in the network. In schedule-based B.A., the minimum energy depletion is required to arrange the schedule. As the network dimension increases, each sensor also consumes more energy. Contention-based B.A. suffers from packet collision when the network competitors increase. Else, periodic traffic, which generates one packet per 60 seconds, has too much interference and cannot send more packets after there are more than 84 network competitors. Figures 3.15 and 3.16 show the information delay of event-driven application under schedule- and contention-based B.A.. The information delay of periodic application is strongly related to the traffic interval and not appropriate for real-time urban application. We will show the result in next subsection. Event-driven application is more sensitive to the bandwidth allocation methods and generally proportional to the duration of duty cycle T_{dc} . From the result, we know that: First, the probability of a packet arriving in k^{th} duty cycle is $p_k \prod_{i=1}^{k-1} (1 - p_i)$ where p_i is the probability that the packet is received in i^{th} cycle. Second, when a packet arrives in k^{th} duty cycle, the arriving time point is uniformly distributed with the mean $\frac{T_{dc}}{2}$. The expectation of information delay of event-driven

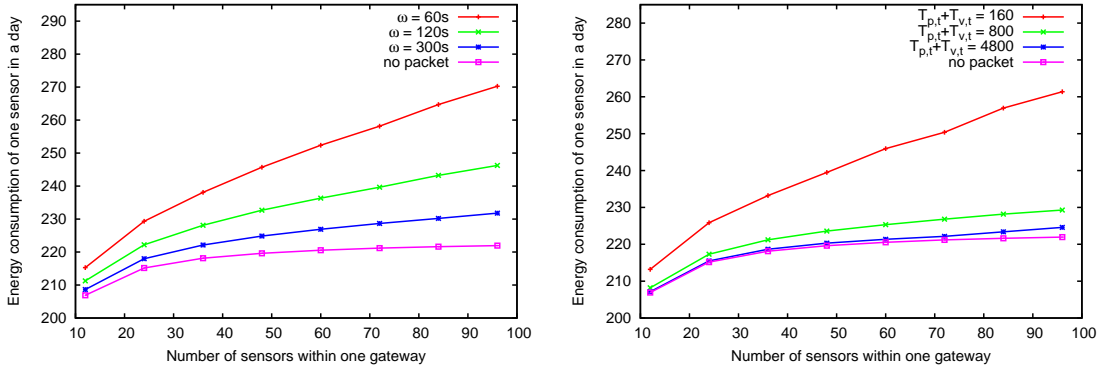


Figure 3.13: Per-node energy consumption of (left) periodic and (right) event-driven applications while varying N and traffic parameters under *schedule*-based B.A.

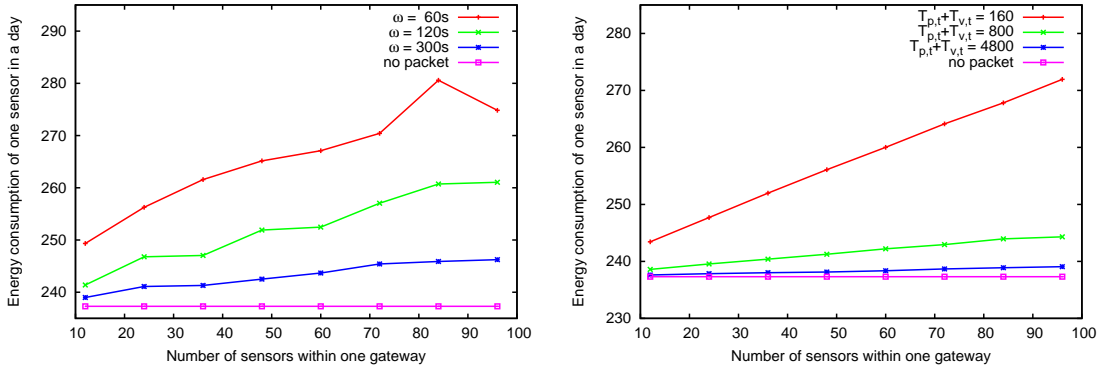


Figure 3.14: Per-node energy consumption of (left) periodic and (right) event-driven applications while varying N and traffic parameters under *contention*-based B.A.

application is calculated as below:

$$E[T_{delay}] = \sum_{k=1}^{\infty} (p_k \prod_{i=1}^{k-1} (1 - p_i)) (k - \frac{1}{2}) T_{dc} \quad (3.8)$$

$$= \frac{p_1 T_{dc}}{2} + \sum_{k=2}^{\infty} (1 - p_1)(1 - p_2)^{k-2} p_2 (k - \frac{1}{2}) T_{dc} \quad (3.9)$$

Here p_i is mainly a function of the network load, duty cycle and resource allocation method. In contention-based protocol, we see that packets have a very low chance to arrive the destination if they do not arrive in first duty cycle. When the network load is affordable for the network, p_1 is quite high and $\{p_i\}_{i=2}^{\infty}$ are all similarly very low. If packets do not arrive within first duty cycle, the delay time starts to be arbitrarily large. That is the drawback of CSMA. In schedule-based protocol, if packets do not arrive in first duty cycle, they still have a good chance to arrive in the coming cycles. In a word, we can get the following equations to calculate the information delay from the results:

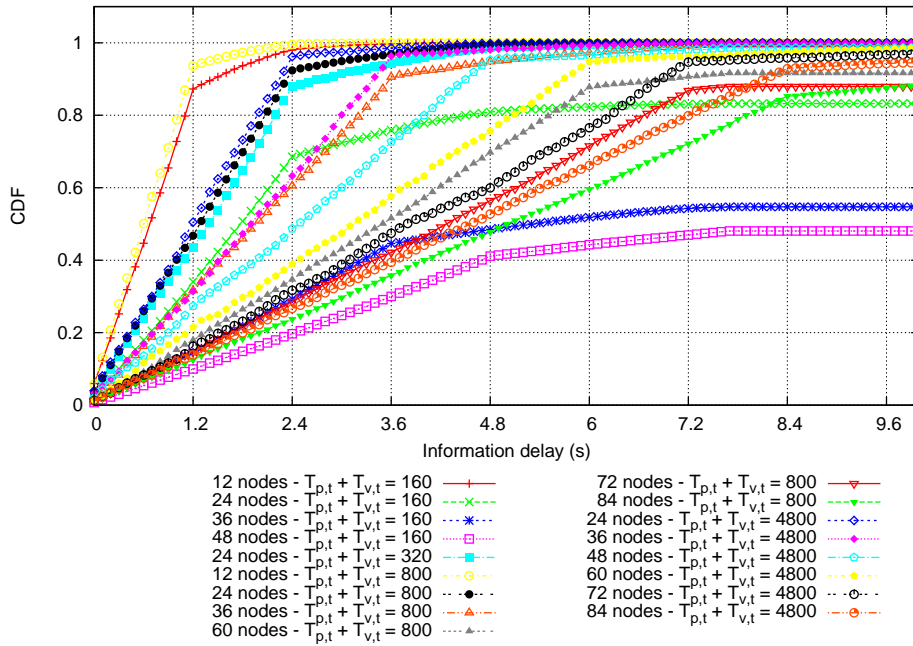


Figure 3.15: Information delay of *event*-driven application while varying traffic parameters and node number under *schedule*-based B.A.

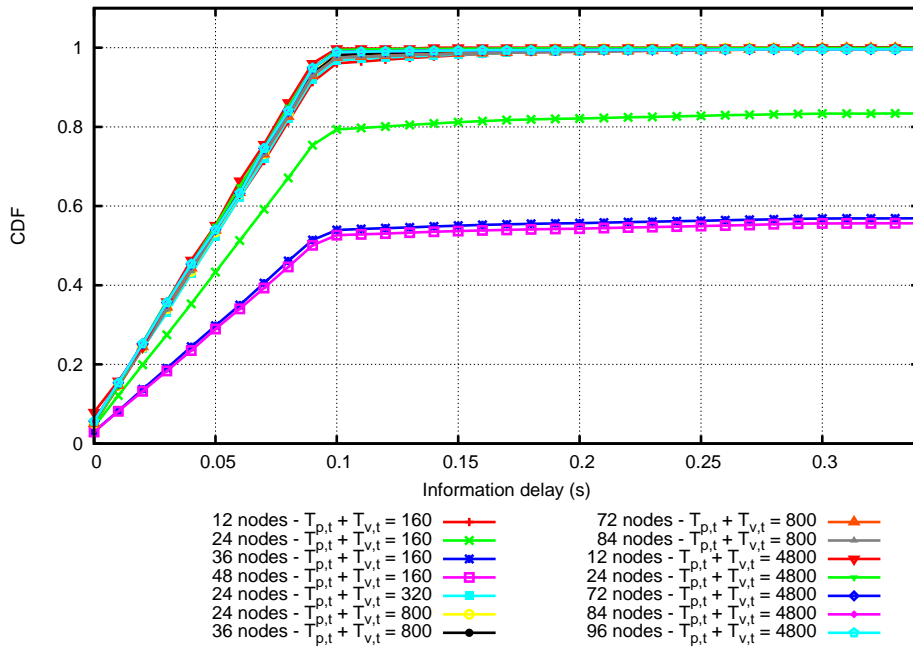


Figure 3.16: Information delay of *event*-driven application while varying traffic parameters and node number under *contention*-based B.A.

$$E[T_{delay.contention}] = T_{dc} \left(\frac{1 - p_1}{p_2} + \frac{1}{2} \right)$$

$$E[T_{delay.schedule}] = T_{dc} \left(\frac{1}{p_1} - \frac{1}{2} \right) \quad \text{for } p_1 = p_2$$

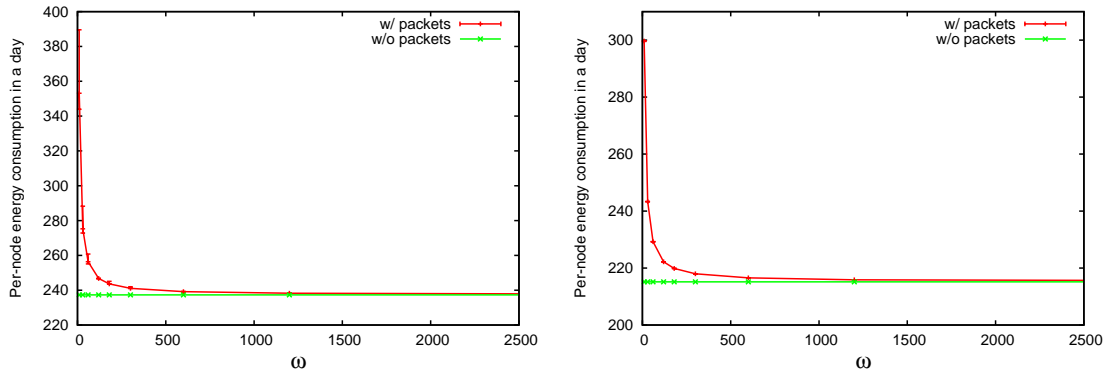


Figure 3.17: Per-node energy consumption: *Periodic* application under (left) contention- and (right) schedule-based B.A. while $N = 24$

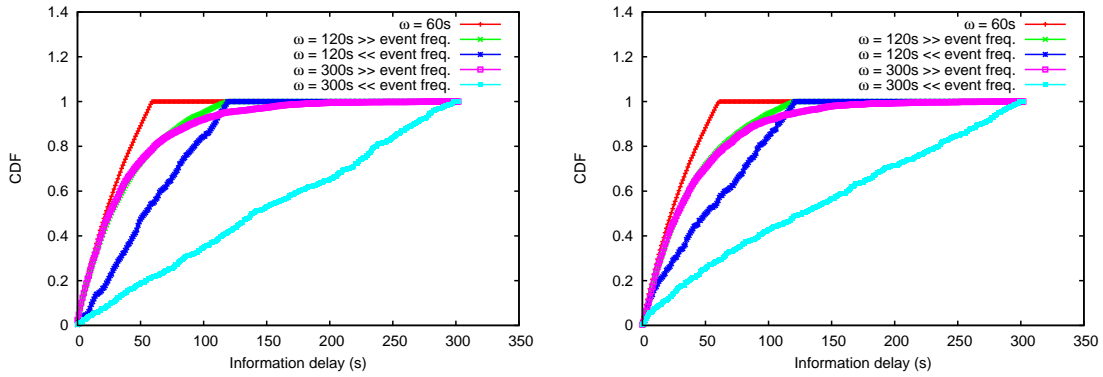


Figure 3.18: Information delay: *Periodic* application while varying traffic parameters ($N = 24$) under (left) contention- and (right) schedule-based B.A.

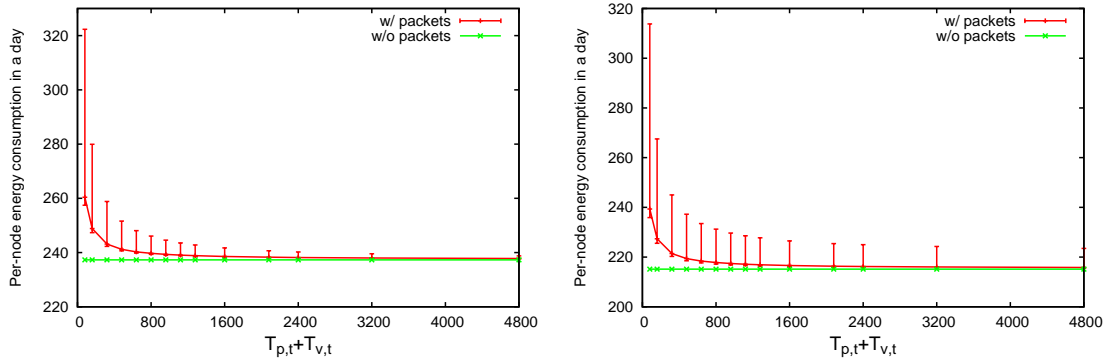


Figure 3.19: Per-node energy consumption: *Event-driven* application under (left) contention- and (right) schedule-based B.A. while $N = 24$

3.6.1.2 Impact of traffic intensity and burstiness

The simulation we ran in this section used the topology depicted in Fig. 3.12(b) with 24 nodes. Fig. 3.17 shows the relationship between traffic interval ω and per-node energy

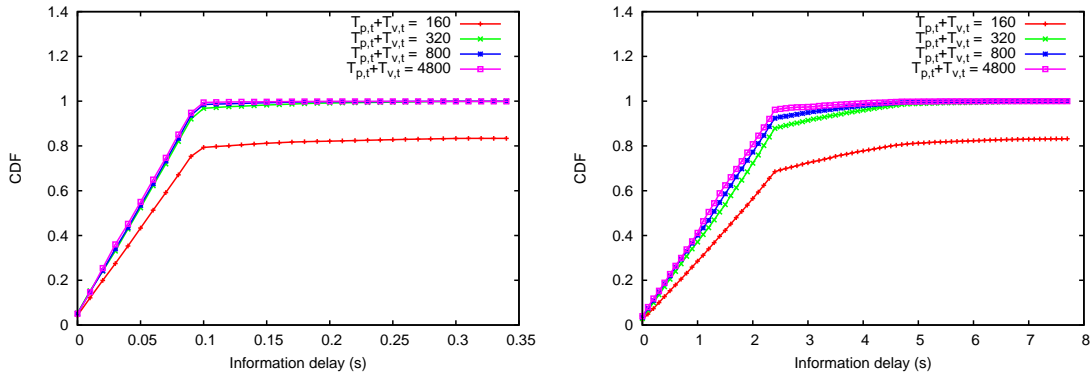


Figure 3.20: Information delay: *Event-driven* application while varying traffic parameters ($N = 24$) under (left) contention- and (right) schedule-based B.A.

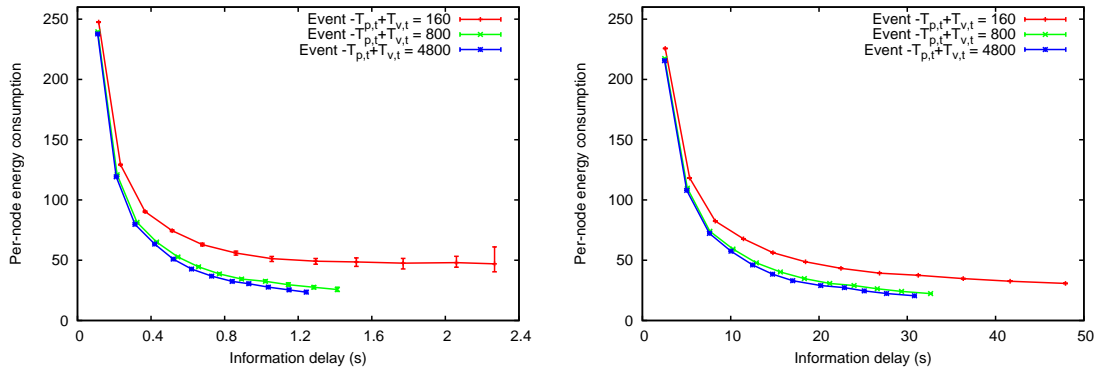


Figure 3.21: Per-node energy-delay trade-off of event-driven application in (left) contention- and (right) schedule-based B.A. while $N = 24$

consumption, we see that periodic traffic is less affected by the B.A. method and strongly related to the traffic interval. The periodic traffic is equivalent to constant bit rate so that the traffic is known and uniform among all sensor nodes. Hence the deviation of consumed energy is not apparent. In Fig. 3.18, we see that the information delay between periodic and event-driven applications is not that different. Since the arriving time point during the traffic interval is uniformly distributed, its expected value can be calculated by the summation of the application-layer delay and MAC-layer end-to-end delay, that is, $\frac{\omega}{2} + T_{dc}(\frac{1-p_1}{p_2} + \frac{1}{2})$. If the event occurrence frequency is much higher than traffic interval, the sensory status could change more than one time in ω seconds. In this way, some update information will be missed if the sensor does not store it into packet and the information delay will be also shorter and exponentially distributed. However, it is obvious that the consumed energy is extremely low while $\omega \geq 1200$. In other words, the information delay which is more than 1200 seconds will not be acceptable for real-time urban services. But it is interesting to assign a periodic traffic with a long interval on sensor nodes simply to inform gateways of their existences and current battery status. On the contrary, event-driven application, affected by Weibull distribution, has a larger variation on packet generation rate, and so does the energy consumption, shown in

Fig. 3.19. The burstiness of Weibull traffic model creates a strong non-uniform traffic on each sensor node because of its infinite variance. Fig. 3.20 shows the information delay while the network dimension is fixed. When the network load is affordable for the network ($p_1 \rightarrow 1$), the information delay is generally proportional to T_{dc} . When we increase the event occurrence rate ($T_{p,t} + T_{v,t} = 4800 \rightarrow 320$), p_1 starts to reduce from 0.96 to 0.88 in schedule-based B.A. and from 0.99 to 0.96 in contention-based B.A.. Even the network load is high, contention-based protocol can still delivery more packets (79%) than schedule-based (68%) in first duty cycle thanks to its dynamic bandwidth allocation method. Schedule-based protocol requires more central information exchange between sensors and network coordinator so that it is much less adaptive to the traffic variation and not preferable for distant sensor nodes.

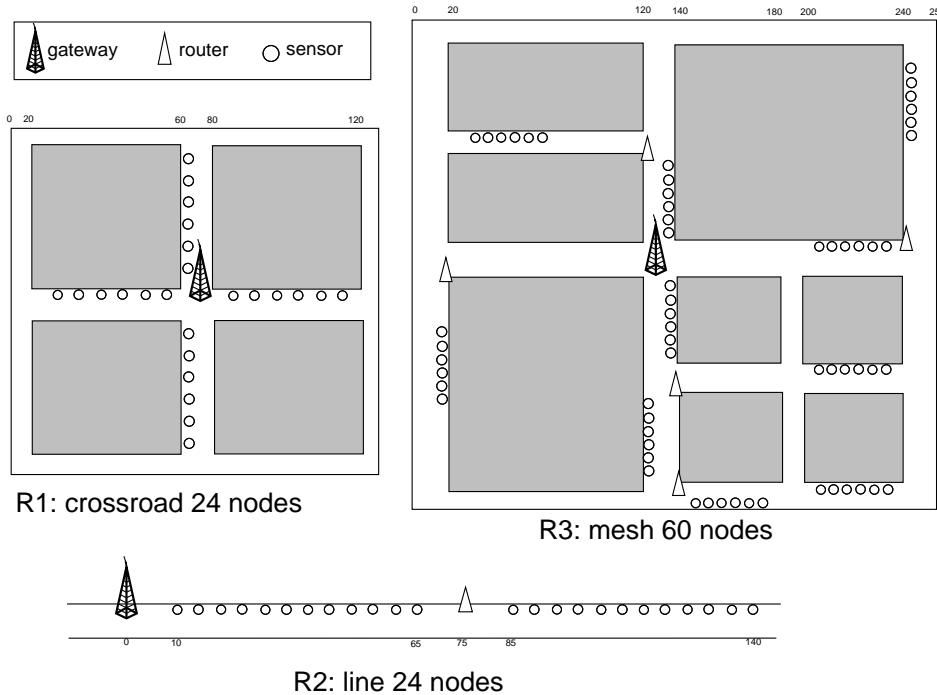
3.6.1.3 Impact of duty cycle

From Fig. 3.21, duty cycle is generally determined by slot duration which is, however, bounded by traffic model. The minimum slot duration $T_{slot.min}$ shall be long enough to complete a reservation and a piggybacked packet transmission so that packet size and data rate are the important factors. Nevertheless, the maximum slot duration $T_{slot.max}$ is limited by the minimum required throughput according to applications carried out in the network. That is to say, if the slot duration is equal to T_{slot} seconds, the maximum throughput will not exceed $\frac{1}{T_{slot}}$ packets per second by assuming that the inactive period is zero. We varied slot duration from 0.1 to 1.2 seconds by applying the topology in Fig. 3.12(b) with 24 nodes and then got the energy-delay trade-off. For $T_{p,t} + T_{v,t} = 160$, $T_{slot.max} \ll 3.33$ considering the routing overhead. Hence, we can see that the energy deviation is more obvious when the slot duration is approximating to $T_{slot.max}$ in contention-based B.A.. That is because the number of data slot decreases with $\frac{1}{T_{slot}}$ and results in more network competitors in each data slot. However, thanks to the extremely low collision rate in schedule-based B.A., the energy deviation is still low even though we increase the slot duration. Accordingly, while having the same slot duration, the energy consumption in contention-based B.A. is a bit higher, yet the information delay is much shorter. In other words, subject to the throughput conditions, for the same information delay, contention-based B.A. consumes significantly less energy than schedule-based one.

3.6.2 Impact of network topology - scenario 2

3.6.2.1 Packet interarrival time

Figures 3.23 and 3.24 show the packet interarrival time of 24 wireless parking sensors in two different topologies, namely crossroad and line types. Compared with Fig. 3.5, the interarrival time is reformed and the average value is until 30 according to the traffic threshold τ which decides when an updated information is delivered. The contention-based protocols restore better the curves to the original form which is the exponential distribution, thanks to its traffic adaptive property. In the topology R2, parts of parking sensors are far away from the gateway and can only reach the gateway by the router in the middle of the street through two-hop. This way, we see that CSMA and i-Queue



- R1 – Crossroad: 1 gateway & 24 parking sensors
- R2 – Line: 1 gateway, 1 router & 24 parking sensors
- R3 – Mesh: 1 gateway, 5 router & 60 parking sensors

Figure 3.22: Three different topologies for our simulations

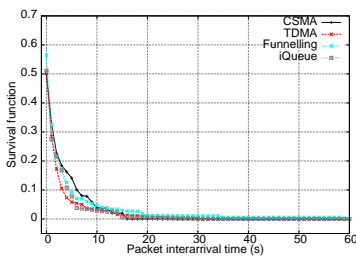


Figure 3.23: The survival function of packet interarrival time on the gateway side: Crossroad

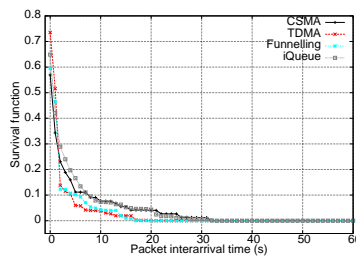


Figure 3.24: The survival function of packet interarrival time on the gateway side: Line

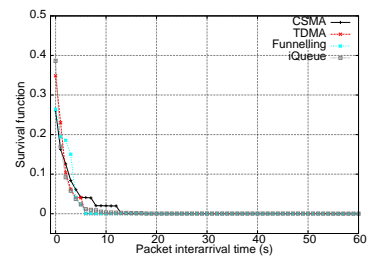


Figure 3.25: The survival function of packet interarrival time on the gateway side: Mesh

MAC both give similar interarrival time which is close to the original form in Fig. 3.24. On the contrary, TDMA and Funnelling, applied schedule-based around the gateway, have a longer delay time and differ from the other two. Also some packet interarrival times are over 30 seconds because of the longer transmission distance. Fig. 3.25 can be regarded as a mix-up of crossroad and line types. As the network size increases, so does the probability of packet arrival. It is obvious that the different MAC protocols cause a slight difference. However, the interarrival time is still approximately an exponential distribution. Hence, the Markov’s queuing model may be possible to apply.

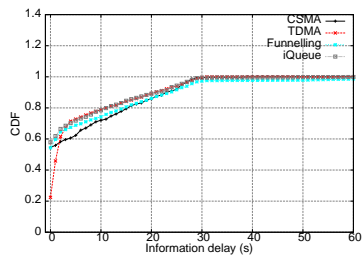


Figure 3.26: The information delay of a changed parking occupancy status: Crossroad

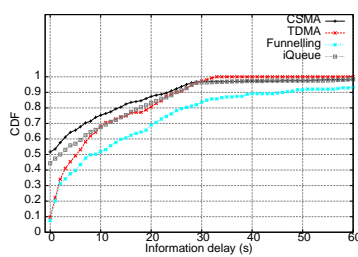


Figure 3.27: The information delay of a changed parking occupancy status: Line

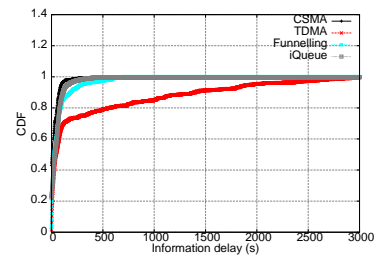


Figure 3.28: The information delay of a changed parking occupancy status: Mesh

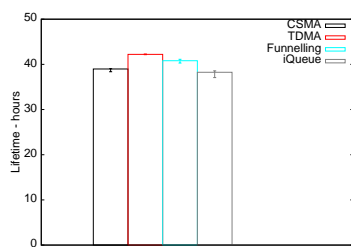


Figure 3.29: The lifetime of parking sensors while $s_D = 0.1s$ and battery capacity 6.3Ah: Crossroad

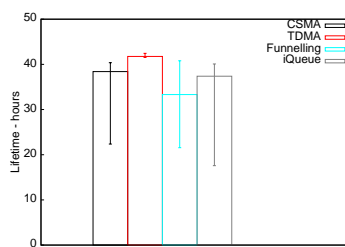


Figure 3.30: The lifetime of parking sensors while $s_D = 0.1s$ and battery capacity 6.3Ah: Line

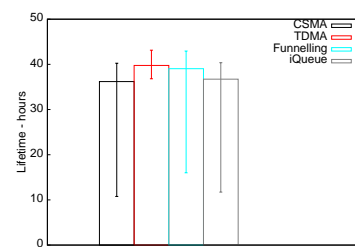


Figure 3.31: The lifetime of parking sensors while $s_D = 0.1s$ and battery capacity 6.3Ah: Mesh

3.6.2.2 Information delay

Smart parking service provides real-time information to drivers thanks to the unceasing parking sensing. Thus, the change of parking occupancy status must arrive at the gateway at a shortest delay. In the topology of R1, each parking sensor can reach the gateway in one hop. In Fig. 3.6 we showed the two turning points of periodic and event-driven hybrid application, namely at the time point of one-time duty-cycle and switching threshold τ . The information delay of the topology R1 is shown in Fig. 3.26, and only TDMA shows clearly the two turning points since its duty-cycle period is longer than the others. While changing to the linear topology R2, TDMA has almost no difference but prolongs its information delay by one-hop more communication. Contention-based protocol basically performs a better delay time in the beginning but then less good than TDMA in the end. Funnelling-MAC assigns the nodes one-hop around a guaranteed time slot uniformly but it does not consider the different traffic loads among them. In R2, the router and all the parking sensors, between the gateway and the router, are all assigned their exclusive time slot once. However, the router, who has to forward all the generated packets in its right side, will have much more packets to send than its neighbors. In a word, there is a bottleneck on the router and it prolongs the network delay time distinctly. i-Queue MAC basically adapts to the network traffic according to the queue indicator. But restricted to the vTDMA period, the contention access period is shortened and it provokes more packet collisions. Normally, the vTDMA period is

expected to help to reduce the CSMA-slot competitors, but it is less common that a node has two consecutive packets with the sporadic traffic in PSNs except the routers. Thus sensors compete in a shorter contention access period and packet collision happens more frequently. Then if we increase the network dimension, it implies that there are more routers around the gateways. The result in Fig. 3.28 shows that i-Queue MAC has a good performance as CSMA but the slot allocation still requires at least one packet transmission in the CSMA time slots of CAP. TDMA has a very long information delay because of its longer duty-cycle and also the construction of multihop scheduling. The schedule can be optimized when the network topology is known.

3.6.2.3 Lifetime

Finally, we look at the autonomy of parking sensor network. The most important is the energy depletion. If the parking sensor cannot live for a long time, the maintenance of the infrastructure will be expensive for the city. We limit the battery capacity to 6300mAh, the slot duration 0.1 seconds and $T_{GTS} + T_{inactive} = 0$, then compare the lifetime of parking sensors under different bandwidth allocation strategies. Fig. 3.29 shows the lifetime in the topology R1 crossroad. Since each parking sensor can reach the gateway through one hop, the packet collision rate is low and so does the energy deviation. Funnelling-MAC is between TDMA and CSMA according to the percentage of TDMA slots (n_{tdma}) and CSMA slots (n_{csma}). Here we added Rayleigh fading in the propagation model and some nodes can probably run in CSMA mode if they do not receive the slot allocation messages in the beginning. i-Queue MAC behaves like CSMA but consumes a bit more energy as a result of few contention time slots and additional size in the i-Queue MAC header.

Fig. 3.30 shows the energy consumption of the linear topology R2. It is obvious that all MAC protocols have a higher energy depletion deviation except TDMA. That is because TDMA is the only contention-free (schedule-based) MAC protocol in our scenarios and half of nodes have to run in multihop network which provokes an hidden terminal problem. Funnelling-MAC has a very bad performance in linear topology due to the unbalanced TDMA slot allocation for the router.

Fig. 3.31 shows the lifetime of parking sensor in mesh topology. The energy depletion variation of TDMA varies more than the other two topologies because the larger network dimension costs more energy during the signaling period. i-Queue MAC benefits from more routers around and reduces the competitors in the network. However, its energy variation is still as much as CSMA. Funnelling-MAC has a quite good energy efficiency in the mesh network if each linear path is not too long. Hence, to improve the Funnelling-MAC, the routing protocol will also be concerned.

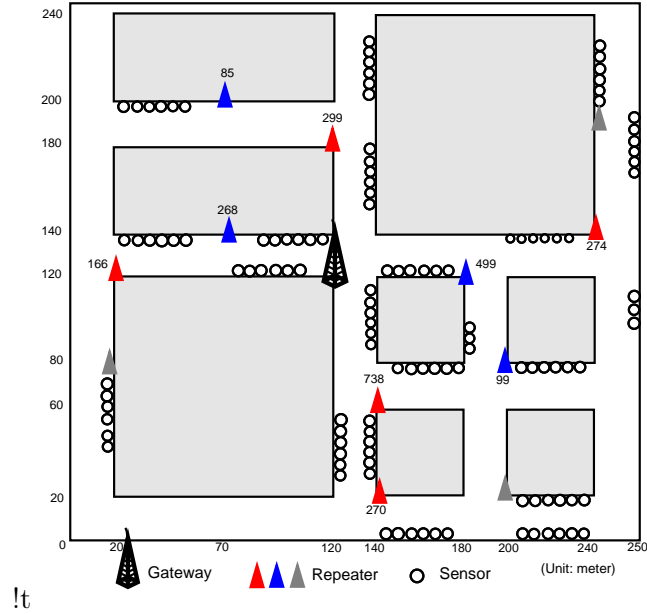


Figure 3.32: Parking Map with 120 parking sensors

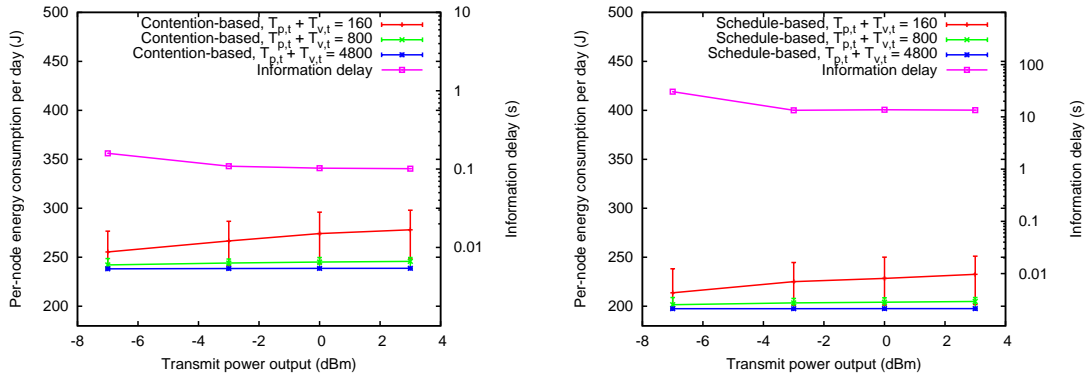


Figure 3.33: Per-node consumed energy and delay of event-driven application under (left) contention- and (right) schedule-based B.A.

3.6.3 Impact of transmission power - scenario 3

3.6.3.1 Impact of multihop

While deploying a large-scale parking sensor network, multihop is inevitable considering the complexity of urban environment and the limitation of transmission range. Since the transmission range is generally proportional to the transmit power output (TPO), to reduce TPO and transmit packets with a shorter transmission distance will be a good idea to extend the lifetime of parking sensors. The longer lifetime the sensor has, the fewer maintenance the municipality has. From the previously discussed in Scenario 1, we see the problem of energy hole and hop limit (delay). For a better consideration, we take a parking map from SFpark [1] and construct it in our simulation depicted in Fig. 3.32. Here, all sensors work as a reduced function device and can only communicate

with repeaters or gateways. Only repeaters and gateway, namely full function device, can forward any received packets until the packet arrives the gateway. Since parking sensor is generally in-ground and repeater can be installed on the streetlight and powered by solar cell, this configuration is greatly preferable to municipalities. With the parking map we have, we first deploy repeaters in each intersection and in the middle of the road section when needed. In this simulation, we take four different TPO = {3, 0, -3, -7} dBm. In Fig. 3.32, the red repeaters are needed when TPO is equal to 3 and 0 dBm. When TPO is -3 dBm, the red, blue and grey repeaters are all needed as well. When TPO is -7 dBm, the grey repeater cannot provide a stable support and have to add some more repeaters to guarantee the quality of service. When TPO is smaller than -10 dBm, the density of repeater will be very high (at least 2 repeaters per road section). The energy and information delay results are shown in Fig. 3.33 while applying contention- and schedule-based B.A.. Also, we get some facts from this experiences: First, the update frequency of gradient routing, which affects the transmission path, shall be high enough according to the dynamic urban environment. Second, the network is divided into several small dimension cells so that contention-based protocol shall be favorable. Third, a minimum TPO is required considering the router deployment limited by the street layout. Fourth, the load of each router, labeled as a numeric in Fig. 3.32, shows that the load balancing is needed for gradient routing; otherwise, certain routers will run out of energy soon.

3.7 Summary

In this section, we summarize our results in Section 3.6 and provide engineering insights to streamline the WSN construction of urban smart parking application. The B.A. method is the utmost important key point of determining energy consumption and information delay when traffic and node densities are known a priori. We applied two fundamental types of B.A. to our simulations instead of choosing particular protocols. In this way, we can see clearly that how the traffic intensity and node density affect the network performance and the results could serve as guidelines for urban sensor network designers. We discuss it separately from the following viewpoints by referring to Fig. 3.34.

- NETWORK TRAFFIC MODELS We showed that the impact of the periodic traffic interval for selecting an appropriate $\omega > 1200$, and then the influence of event triggered application with Weibull distributed vehicle occupancy time. From [224], the shape parameter is always smaller than 1 and heavy-tailed. Weibull distributed packet interarrival time also shows the burstiness and non-uniform packet generation rate of network traffic comparing to exponentially distributed. The traffic characteristics requires a dynamic bandwidth allocation, e.g., contention-based MAC. When the event occurrence frequency is 2 times more than $\omega = 1200$, part of event-driven packets can be combined with the periodic traffic so as to reduce the network load and energy consumption after evaluating the information delay.
- INFORMATION DELAY From the results, the delay time can be calculated by equa-

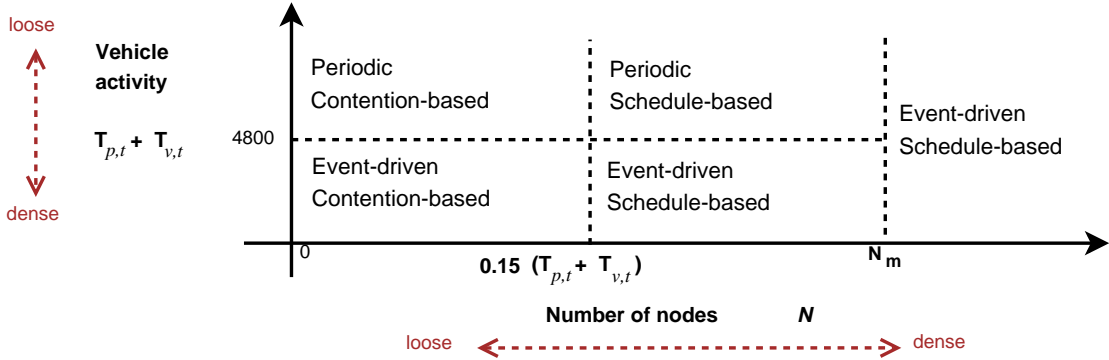


Figure 3.34: Best configuration versus vehicle activity and network density

tion(3.8) and then mainly determined by the probability of arriving in 1st duty cycle (p_1) and the duration of duty cycle (T_{dc}). In schedule-based B.A., if packets do not arrive in 1st duty cycle, they can still have quite high chance to arrive in 2nd or 3rd duty cycle. In contention-based B.A., the packets, which do not arrive in 1st duty cycle, will probably never arrive or have a very long information delay due to the exponential backoff time. Thus, while the ratio of network dimension to network load is higher than 0.3, schedule-based B.A. shall be applied to ensure the packet delivery ratio. $N = 0.3 * \frac{1}{2} * (T_{p,t} + T_{v,t}) = 0.3(\frac{1}{2}\lambda\gamma(1 + \frac{1}{\alpha}) + \frac{1}{2}\mu\gamma(1 + \frac{1}{\beta}))$.

- **ENERGY-DELAY TRADE-OFF** The energy consumption is proportional to network dimension, traffic variation and duty cycle. The duty cycle is generally determined by slot duration and limited by $T_{slot.max} < \frac{1}{N}(\frac{1}{2}\lambda\gamma(1 + \frac{1}{\alpha}) + \frac{1}{2}\mu\gamma(1 + \frac{1}{\beta}))$. While giving a desired information delay, contention-based MAC consumes much less energy. What will happen if the network traffic and node densities are both high? T_{dc} shall be greater than $\frac{2}{T_{p,t}+T_{v,t}}$ or $\frac{1}{\omega}$ respectively. Since $\frac{2}{T_{p,t}+T_{v,t}} \ll \frac{1}{2\omega}$ to apply periodic application, certainly $\frac{1}{\omega}$ exceeds T_{dc} faster than $\frac{1}{2\omega}$. By assuming N_m is the maximum number of nodes to apply periodic application in schedule-based B.A., we have $((N + 1) * T_{slot} + T_{inactive})^{-1} = \frac{1}{\omega}$. Thus, $N_m = \frac{\omega}{T_{slot}} - 1$ if $T_{inactive} = 0$.
- **TRANSMIT POWER OUTPUT** The PSN architecture introduced in subsection 3.6.3.1 is good for extending the lifetime of in-ground sensor nodes. Based on this, the communication range is significant for router/gateway deployment. A minimum TPO is required for sensor nodes so as to reach these routers or gateways in cross-roads.
- **LOAD BALANCING** In multihop network, the routing path is maintained by gradient routing. From the results in Fig. 3.32, we see the network load in each router is highly non-uniform. The load balancing shall be considered into the implementation of routing protocol.

Then, we studied the wireless parking sensor networks from the viewpoint of network traffic and MAC protocols. The traffic model is generally affected by vehicle's arrival and departure which are both heavy-tailed. While looking at a group of parking sensors,

the simulation shows that the packet interarrival time is no longer heavy-tailed but exponentially distributed, which might help the reuse of Markov's queueing model. Then we chose four different types of MAC protocols and evaluated them in 3 kinds of network topologies. The result show that an hybrid adaptive MAC can help to improve the network performance by providing a better energy-delay trade-off. However, it can also drop the network performance when the topology changes. Funnelling-MAC is a quite good choice for the crossroad and mesh topologies, but not for a long linear one. The other hybrid MAC protocol, i-Queue MAC, only works well in small cell and one-hop network because the burstiness of PSN is caused by increasing transmitters, not the traffic load of one sensor node. The important criteria of choosing an appropriate MAC protocol are to consider the deployment of sensors and routers which connect to gateway directly and their traffic models, like the packet interarrival time can presents the bursty network traffic on different groups of nodes. From the result, it also shows that the information delay is bounded by application and MAC parameters, even with the bursty traffic generated by Weibull distribution.

Deployment of Urban Infrastructure

4.1 Introduction

As traffic congestion increases in cities, a smart parking system that assists drivers to find a parking place is of vital importance. There are plenty of low-cost off-street parking solution available in the market, but there is still not an optimal solution

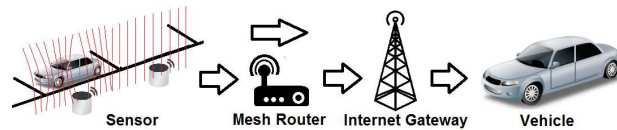


Figure 4.1: Smart parking information flow

for on-street parking. Some cities have started their smart parking projects, e.g., SFpark (San Francisco) [1] and SmartSantander (Santander) [135]. These cities adopt a sensor-enabled on-street parking system that installed ferromagnetic parking sensor on each spot and indicate its vacancy. To obtain the parking occupancy status, sensors can send messages via either long-range communication, like Sigfox or LoRa, or short-range communication, such as 802.11ah, low-power WiFi or Zigbee. These parking detection sensors are mostly installed underground and it is costly to replace their battery. A common objective is that each sensor should be autonomous for at least 5-20 years. Long range low-power cellular networks give great energy efficiency thanks to the ultra-narrow band technology, but it is limited in terms of bandwidth and reactivity, e.g., Sigfox nodes can send at most 140 12-byte transmission messages a day. In a previous work [86], we have shown that the generated messages for smart parking application follow a heavy-tailed distribution [135]. The limits of low-power cellular networks can be overpassed by the sensors in the most dynamic parts of cities. In such settings, the short-range communication that provides more capacity at low-power energy levels is usually favorable. In this work, we consider a city-wide wireless mesh infrastructure (WMI) comprising mesh routers (MR) and Internet gateways (IGW). The deployment of WMI networks at a citywide level with reasonable costs [229] is the primary concern. Due to the limitation of the soil medium and battery energy [220], the underground sensors communicate directly with roadside overground MRs or IGWs. Sensors, MRs and IGWs form wireless parking sensor networks in metropolitan areas and provide real-time information to users in Fig. 4.1. The deployed sensors are generally scattered with a minimum adjacent distance of 2 – 5 meters (angle or parallel parking) in order to avoid multiple detections. The network topology is mostly linear and uniform along the street layout. In Fig. 4.2, we see that MR (repeater) and IGW (gateway) are mostly installed at crossroads in the real-life deployment because most traffic panels are installed at crossroads with electrical cable. Some sensors might be too far from MR/IGW, thus multispace parking meters are often used as a network

relay. MR/IGW can also benefit from the line-of-sight situation to reach the maximum coverage. As IGW (2000 €) provides more functionality as an Internet portal, it is more expensive than MR (10 €), which simply serves as a relay or message collector [5]. There are three main characteristics of the deployment of smart parking sensor network: energy, connectivity and timeliness.

Our previous study [86] shows the essential issues when constructing parking sensor networks in urban areas: in-ground sensor lifetime, network connectivity, load balancing of WMI and sensing information delay. These issues correlate with the two following deployment problems: The first is the WMI deployment: Sensor lifetime is generally affected by the radio module on sensor boards, especially the wireless transmission power. The transmission power depends upon the transmission distance from a sensor itself to the closest WMI. To ensure its connectivity, a minimum transmission power will be applied. This means a denser WMI deployment will help extend a sensor's lifetime. Second is the IGW deployment: In a multi-hop mesh network, each MR has to process its own packets and those from their descendants. A longer route path increases network load, packet loss rate and information delay. Thus, load balancing and network delay both have to be both taken into account when deploying IGWs.

Our contribution is to formulate the problem of deploying a smart parking multi-hop mesh networks within city infrastructure and solve it with a multi-objective optimization approach. We also highlight the following insights on the design of parking sensor network: First, the sensor's total energy is determined by the amount of intersections and is inversely proportional to the number of active WMIs. Second, the sensing information delay is related to the average degree of complexity of the street-parking graph. Thus, the complexity of city street layout is an important factor while building urban infrastructure. Third, the IGW deployment can be seen as a cluster problem on parking sensors' geographical position. Once the selection of WMI is done, the cluster number will be the minimum amount of deployed IGWs. Fourth, we show the trade-offs between sensor's lifetime, information delay and the cost of city infrastructure to be provided as a guideline, and take it into account while integrating with the pre-existing infrastructure.

4.2 Related works

From literature, the network performance is strongly determined by the density of MR and IGW. Marks [230] highlights the most important objectives while deploying wireless sensor networks. He *et al.* [231] studied the relationship between MR/IGW capacity and deployed amount using two tree set partitioning approaches. Li *et al.* [232] proposed a grid-like gateway deployment to achieve the optimal throughput. This method is somehow similar to a crossroad-based deployment. Konstantinidis *et al.* [233] and Syarif *et al.* [234] both proposed a multi-objective evolutionary approach to aid the sensor deployment. [235] optimized the IGW deployment with a multi-objective problem as well. However, we do not see an actual map of real world street being considered in a multi-objective optimization. In this chapter, we are mainly interested in the impact of

the map on the deployment of city infrastructure. We consider a multi-objective problem and optimize it by using the real on-street parking maps.

4.3 Gateway & router deployment

To analyze the problem above, we propose the following methodology: We define four objectives in our scenario: energy, connectivity, cost and latency of the multi-hop mesh network. From these constraints, we can also get some parameters, which are relevant to sensor's lifetime and sensing information delay. We build two graphs: an on-street parking network and a wireless link set, to indicate the relationship between any two given intersections. We then consider two different maps, which have the same length of street parking area, but with completely different street layout. Finally, we take the adjacency matrices as the data inputs of our constraints and try to optimize them.



Figure 4.2: The deployment of SFpark[1]

4.3.1 Multi-hop modeling

We define the graph of a city by the set of street intersections (V) and the set of road segments (E) between them. Then, $C = (V, E)$ represents city graph. For all v_i and $v_j \in V$, we give two binary variables to express the status of each crossroad v_i by Eqs. 4.1 and 4.2:

$$x_i = \begin{cases} 1 & \text{if a WMI is installed in } v_i \\ 0 & \text{otherwise} \end{cases} \quad (4.1)$$

$$y_i = \begin{cases} 1 & \text{if an IGW is installed in } v_i \\ 0 & \text{otherwise} \end{cases} \quad (4.2)$$

The amounts of deployed WMIs and IGWs are expressed in Eq. 4.3 and 4.4 respectively. In such a case, there are $(\phi_x - \phi_y)$ MRs. For formulating our deployment problems, we define some variables in Table 4.1.

$$\phi_x = \sum_{i \in V} x_i \quad (4.3)$$

$$\phi_y = \sum_{i \in V} y_i \quad (4.4)$$

V	$\{v_0, v_1, \dots\}$ list of intersections
E	list of road segments where are parking places
W	list of wireless links between each intersection
$d_{i,j}$	segment distance between v_i and v_j
d_{max}	maximum road segment length
Ω_s	per-sensor energy consumption
Ω_{WMI}	per-WMI energy consumption
$\rho_{i,j}$	sensor density uniformly distributed on the road segment between v_i and v_j
f_i	packets aggregated from WMI in v_i (packets/s)
$\Gamma_{i,j}$	the managed length on road segment (i,j) on the WMI in the intersection v_i
$k_{i,j}$	the managed sensor amount of each road segment around the intersection v_i
h_i	path distance (hop count) from WMI in v_i to the its corresponding IGW
M_{ns}	maximum sensor numbers per MR
M_{mr}	maximum capacity of MR (packets/s)
M_{igw}	maximum capacity of IGW (packets/s)
M_{hop}	maximum hop count

Table 4.1: Variable index for deployment constraints

4.3.1.1 WMI deployment and sensor lifetime

If a WMI is installed in v_i , it can manage a part of the sensors deployed in the adjacent road segment (i, j) . We assume that it manages a segment of length $\Gamma_{i,j}$ starting at v_i . As a consequence, the sum of the partial segments managed by both intersections has to be greater than the length of road segment (Eq. 4.5). Moreover, the road length managed by each WMI cannot be greater than the road segment (Eq. 4.6 and 4.7). The density of parking sensors varies according to the parking type. For example, in a common parallel parking, the average distance between adjacent parking sensors is 5 meters, thus sensor density $\rho_{i,j}$ is 0.2. In Eq. 4.8 the amount of sensors managed on each WMI can be calculated by the sum of each managed road length multiplied by sensor density. M_{ns} is limited by the bandwidth allocation/scheduling method, e.g., a contention-based MAC protocol cannot serve more than 70 sensor nodes simultaneously when the traffic intensity is high. In Eq. 4.9, if $\Gamma_{i,j}$ is not zero, it implies that there must be one WMI in v_i which manages one part of road segment (i, j) . d_{max} is a normalizing constant greater than all road segments.

$$\Gamma_{i,j} + \Gamma_{j,i} \geq d_{i,j} \quad \forall (i, j) \in E \quad (4.5)$$

$$\Gamma_{i,j} \leq d_{i,j} \quad \forall (i, j) \in E \quad (4.6)$$

$$\Gamma_{i,j} \leq (1 - 0.5 \cdot x_j) \cdot d_{i,j} \quad \forall (i, j) \in E \quad (4.7)$$

$$\sum_{(i,j) \in E} \Gamma_{i,j} \rho_{i,j} \leq M_{ns} \quad \forall i \in V \quad (4.8)$$

$$x_i \geq \Gamma_{i,j} / d_{max} \quad \forall j \in V \quad (4.9)$$

$$k_{i,j} = \lfloor \Gamma_{i,j} \rho_{i,j} \rfloor \quad \forall (i, j) \in E \quad (4.10)$$

Once we get $\Gamma_{i,j}$, the amount of parking sensors managed by v_i on the road segment (i, j) is $k_{i,j}$ (Eq. 4.10). In [86], we remarked that sensor's power consumption mainly comes from the transmission packets correlating with the traffic intensity. Sensors mainly

transmit their sensed information to WMI and only receive control messages from WMI, thus each sensor has a similar reception power $P_{rxmw.s.i}$. Since each sensor has to be aware of any happening around itself, it always applies a sensing cycle for event detection. It costs $P_{sensingmw.s.i}$, which is similar in every sensor because it is very low. We assume that each sensor (initialed s) has a transmission power determined by the transmission distance so that the total energy consumption is shown in Eq. 4.11. Obviously, to minimize $\Omega_{s.total}$, we shall optimize $k_{i,j}$, which is proportional to $\Gamma_{i,j}$. That is why deploying more WMIs can improve the energy efficiency of in-ground sensors.

$$\begin{aligned}
\phi_{\Omega_s} = \Omega_{s.total} &= \sum_{v_i \in V} \sum_{s \in v_i} \Omega_{s.i} = \sum_{v_i \in V} \sum_{s \in v_i} \Theta(P_{txmw.s.i} + P_{rxmw.s.i} + P_{sensingmw.s.i}) \\
&= \sum_{v_i \in V} \sum_{s \in v_i} \Theta(10^{\frac{P_{txdbm.s.i}}{10}}) = \sum_{v_i \in V} \sum_{s \in v_i} \Theta(d_{s,i}^{\frac{1}{10}}) = \sum_{v_i \in V} \sum_{(i,j) \in E} \sum_{l=1}^{k_{i,j}} \Theta\left(\left(\frac{l}{\rho_{i,j}}\right)^{\frac{1}{10}}\right) \\
&= \sum_{v_i \in V} \sum_{(i,j) \in E} \sum_{l=1}^{k_{i,j}} \Theta(l) = \sum_{v_i \in V} \sum_{(i,j) \in E} \Theta\left(\frac{1}{2}k_{i,j}(k_{i,j} + 1)\right)
\end{aligned} \tag{4.11}$$

4.3.1.2 IGW deployment and sensing information delay

The establishment of a multi-hop network is the main concern in this part. Here, we first define some binary variables to express the relationship between intersections in Eqs. 4.12–4.14. For a node, its parent is the node that has direct communication and forward its packets to the Internet; its ancestor is the node which involves in forwarding its packets to the Internet; its IGW is its portal of the Internet.

$$b_{i,j} = \begin{cases} 1 & \text{if WMI in } v_j \text{ is parent of the one in } v_i \\ 0 & \text{otherwise} \end{cases} \tag{4.12}$$

$$a_{i,j} = \begin{cases} 1 & \text{if WMI in } v_j \text{ is ancestor of the one in } v_i \\ 0 & \text{otherwise} \end{cases} \tag{4.13}$$

$$g_{i,j} = \begin{cases} 1 & \text{if IGW in } v_j \text{ manages MR in } v_i \\ 0 & \text{otherwise} \end{cases} \tag{4.14}$$

In the wireless urban sensor network, a gradient-based routing is often adopted thanks to its fewer control messages. Each sensor can forward a packet to its available neighbor with the smallest height (shortest network distance) [236]. We define the multi-hop constraints according to the gradient-based routing protocol. Once the intersections to install WMIs are decided, we will choose some to install IGWs and keep the remains for MRs (Eq. 4.15). In Eq. 4.16, each node cannot be its own parent. If v_j is the parent of v_i , it is its ancestor as well (Eq. 4.17). However, it will not be the child of v_i simultaneously (Eq. 4.18). In Eq. 4.19, each MR has only one parent-node, and each IGW has no parent.

$$y_i \leq x_i \quad \forall i \in V \quad (4.15)$$

$$b_{i,i} = 0 \quad \forall i \in V \quad (4.16)$$

$$b_{i,j} \leq a_{i,j} \quad \forall (i,j) \in W \quad (4.17)$$

$$b_{i,j} + b_{j,i} \leq W_{i,j} \quad \forall (i,j) \in W \quad (4.18)$$

$$\sum_{v_j \in V} b_{i,j} = x_i - y_i \quad \forall (i,j) \in W \quad (4.19)$$

In Eq. 4.20, each WMI is its own ancestor. In Eqs. 4.21, if $a_{i,j}$ is equal to 1, it implies that there are WMIs installed both in v_i and v_j . In Eq. 4.22, v_i and v_j cannot be the ancestor of each other at the same time, i.e., the link is unidirectional. In Eq. 4.24, each IGW is managed by itself. In Eq. 4.25, if $g_{i,j}$ is equal to 1, it implies that there is an IGW installed v_j . Since each IGW manages itself, it cannot be directed by another IGW (Eq. 4.26). In Eq. 4.23, if the IGW in v_j manages the MR in v_i , the IGW is the ancestor of the MR. In Eq. 4.27, each MR is managed by exact one IGW.

$$a_{i,i} = x_i \quad \forall i \in V \quad (4.20)$$

$$a_{i,j} \leq x_i, a_{i,j} \leq x_j \quad \forall i, j \in V \quad (4.21)$$

$$a_{i,j} + a_{j,i} \leq 1 \quad \forall i \neq j \in V \quad (4.22)$$

$$g_{i,j} \leq a_{i,j} \quad \forall i \in V \quad (4.23)$$

$$g_{i,i} = y_i \quad \forall i \in V \quad (4.24)$$

$$g_{i,j} = y_j \quad \forall i \in V \quad (4.25)$$

$$g_{i,j} + g_{j,i} \leq 1 \quad \forall i \neq j \in V \quad (4.26)$$

$$\sum_{v_j \in V} g_{i,j} = x_i \quad \forall i \in V \quad (4.27)$$

In Eq. 4.28, if the MR in v_i is the child of the one in v_j and the descendant of the one in v_k , the MR in v_j is the descendant of the one in v_k as well. In Eq. 4.29, if the MR in v_i is the descendant of the one in v_j and managed by the IGW v_k , the MR in v_j is also managed by the IGW in v_k . Hence, the hop distance of WMI in v_i can be counted by the amount of its ancestors (Eq. 4.31). M_{hop} is the maximum hop distance in the network (Eq. 4.30).

$$b_{i,j} + a_{i,k} \leq a_{j,k} + 1 \quad \forall i, j, k \in V \quad (4.28)$$

$$a_{i,j} + g_{i,k} \leq g_{j,k} + 1 \quad \forall i, j, k \in V \quad (4.29)$$

$$h_i \leq M_{hop} \quad \forall i \in V \quad (4.30)$$

$$\sum_{v_j \in V} a_{i,j} = h_i \quad \forall i \in V \quad (4.31)$$

The average sensing information delay is calculated by the average hop count, which we

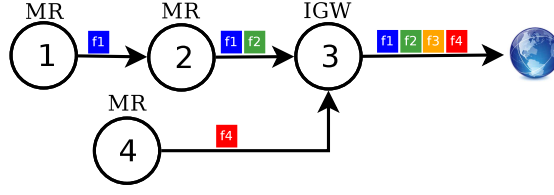


Figure 4.3: An example of a multi-hop network

divide the sum of the required hop counts of each WMI by the amount of WMI (Eq. 4.32). Fig. 4.3 gives an example of 4 WMIs: Node 3 is the Internet portal for all the others; Node 2 and 4 connect directly to node 3; Node 1 connect to node 3 via node 2. Then, node 2 is the parent of node 1; node 3 is the parent of node 2 and 4; node 2 and 3 are both the ancestors of node 1 and node 3 is the ancestor of node 4. Fig. 4.4 shows the values of $a_{i,j}$, $b_{i,j}$ and $g_{i,j}$ when they are equal to 1. h_i signifies the hop count from the sensors managed by MR_i to its IGW.

$$\phi_{h/x} = \left(\sum_{v_i \in V} h_i \right) / \left(\sum_{v_i \in V} x_i \right) \quad (4.32)$$

	[MR 1] →	[MR 2] →	[IGW 3]	← [MR 4]
if $b_{i,j} = 1$:	$b_{1,2}$	$b_{2,3}$	X	$b_{4,3}$
if $a_{i,j} = 1$:	$a_{1,1}, a_{1,2}, a_{1,3}$	$a_{2,2}, a_{2,3}$	$a_{3,3}$	$a_{4,4}, a_{4,3}$
if $g_{i,j} = 1$:	$g_{1,3}$	$g_{2,3}$	$g_{3,3}$	$g_{4,3}$
$h_i = \sum a_{i,j}$:	$h_1 = 3$	$h_2 = 2$	$h_3 = 1$	$h_4 = 2$

Figure 4.4: An example of the variables for the multi-hop network in Fig 4.3

Network capacity can be expressed in Eq. 4.33. According to the network distance of each MR, the collected packets will be re-transmitted h_i times, which generate more traffic on each ancestor. Thus the traffic capacity will be restricted by the maximum capacity of each WMI, i.e., M_{igw} and M_{mr} for IGW and MR, respectively. Packet generation rate f_i depends on the vehicle's arrival and departure. This process has been shown to have a heavy-tailed distribution similar to the Weibull distribution [135]. In Eq. 4.34, the energy consumption is estimated to be proportional to the WMI's capacity, IGW amount and traffic intensity.

$$\sum_{v_i \in V} f_i a_{i,j} \leq M_{mr} + y_j (M_{igw} - M_{mr}) \quad \forall j \in V \quad (4.33)$$

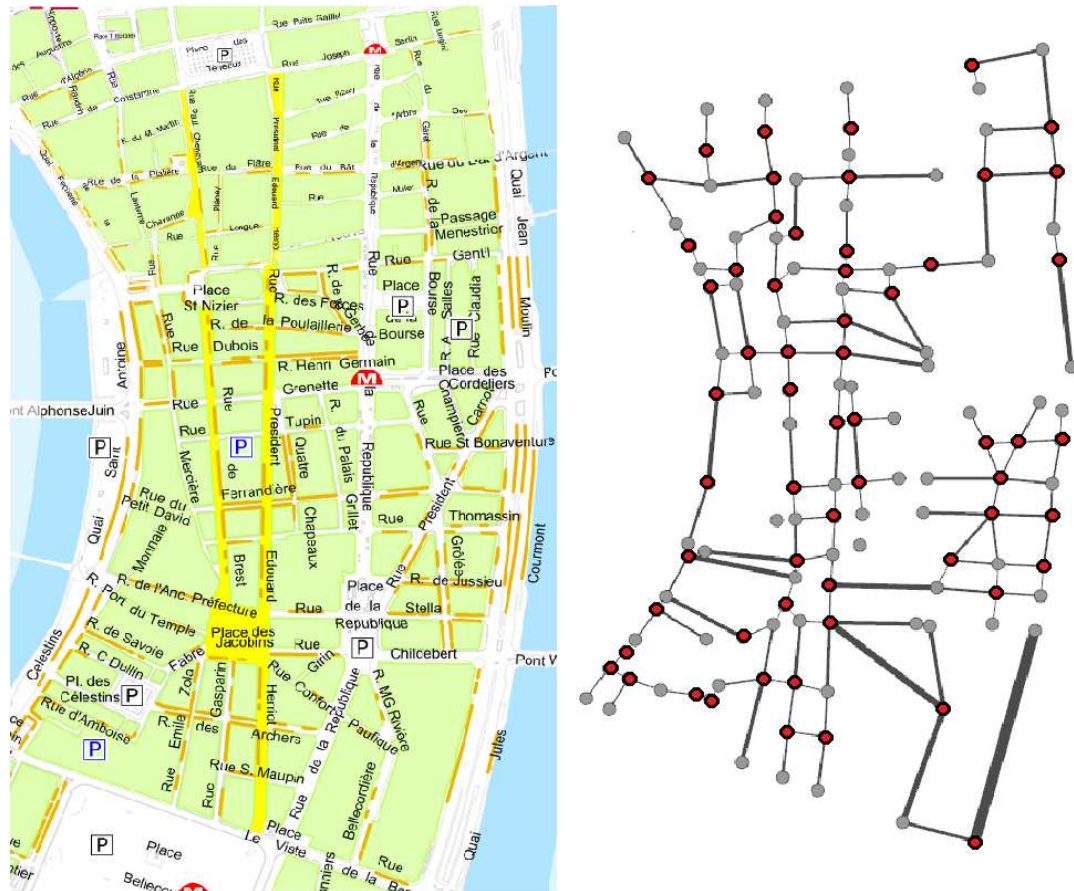


Figure 4.6: Map 2 – Lyon on-street parking map between Place Terreaux and Place Bellecour. The red dots indicate the selected intersections to install WMIs.

4.3.2 Map retrieval

Before resolving our problem in Sage, we took the city OSM file from OpenStreetMap¹. Then with Osmosis², we filtered the unnecessary information and keep only the streets and intersections. Then we trimmed the street map with respect to the parking map in Lyon City’s website. Figs. 4.5 and 4.6 shows the graph from our retrieved map in Gephi³. We used Osm2pgrouting⁴ and pgRouting⁵ to calculate the distance between intersections, i.e., vertexes in our graphs. By referring to [227], we only keep the line-of-sight wireless links in W . Two maps are retrieved and depicted in Figs. 4.5 and 4.6. Map 1 has a grid-like parking distribution. Map 2 is less regular because of pedestrian areas. The total parking area length in both maps is approximately the same. However, map 2 has 27% more crossroads than map 1.

¹www.openstreetmap.org

²wiki.openstreetmap.org/wiki/Osmosis

³gephi.github.io

⁴wiki.openstreetmap.org/wiki/Osm2pgrouting

⁵pgrouting.org

4.4 Multiple-objective optimization

We propose two kinds of optimization methods: First, deterministic optimization assumes a blank area without any pre-existing WMIs. Second, stochastic optimization considers a set of pre-existing WMIs and calculates how many additional WMIs we shall expect to install. Then, we test our methods on the two different street layouts obtained in Section 4.3.2.

4.4.1 Network architecture

In [86], we have studied parking sensor networks and provided the best configuration under different bandwidth allocation methods. Considering the collision problems and the traffic intensity, we compared the energy consumption with different scenarios. A schedule-based media access control protocol and an event-driven application are the most suitable for our scenarios in map 1 and 2. Thus, we assume a pre-scheduled transmission time for all sensors and MRs, and then we focus on the relationship of the multi-hop networks.

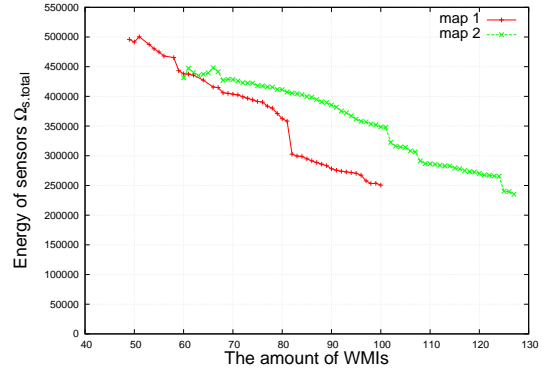


Figure 4.7: Total sensor energy consumption (sensor’s lifetime) v.s. the amount of deployed WMIs (cost)

4.4.2 Characteristics of maps

In Figs. 4.5 and 4.6, the red dots on the nodes are optimal intersections to install WMIs, i.e., x_i equals to 1. The minimum amounts of required WMIs are 49 (over 100 intersections) and 60 (over 127 intersections) in map 1 and 2 respectively. Map 1 has a quite uniform length among all the road segments, and Map 2 has an irregular road length and most of them are very short. With the similar amounts of underground sensors, the cost of map 2 is higher because more WMIs are required to guarantee the network coverage. Thus, we see that the cost of deploying WMIs is positively correlated to the number of intersections.

4.4.3 Energy efficiency

From the set of x_i , we got $\Gamma_{i,j}$ and calculated the energy indicator in Eq. 4.11. Since the amount of WMIs signifies the cost of mesh infrastructure, Fig. 4.7 shows the relationship between the cost and sensor’s lifetime. As the WMI increases, the energy depletion decreases due to the closer transmission distance between sensors and WMI. Two curves both drop when the deployed amount of WMI accounts for 80% of the intersections. Since the road segments are longer in map 1, more sensors have a larger transmission range, hence a higher transmission power. Thus, the maximum energy consumption in map 1 is higher than the one in map 2 in the beginning. Conversely, map 1 has fewer intersections and is covered faster than map 2 by the WMI. We concluded that the

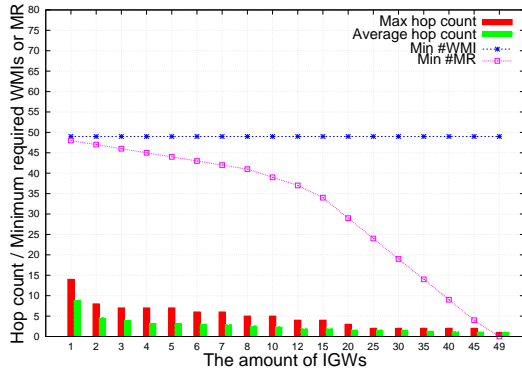


Figure 4.8: Average hop count (information delay) v.s. the amount of deployed IGWs (cost) in map 1

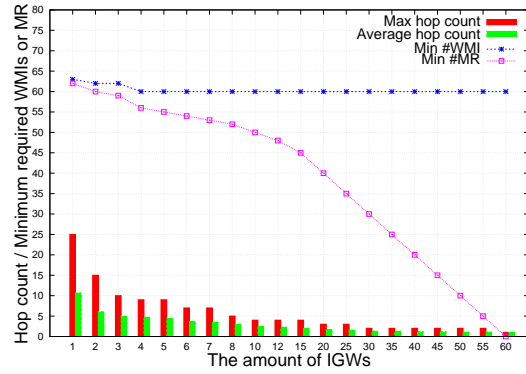


Figure 4.9: Average hop count (information delay) v.s. the amount of deployed IGWs (cost) in map 2

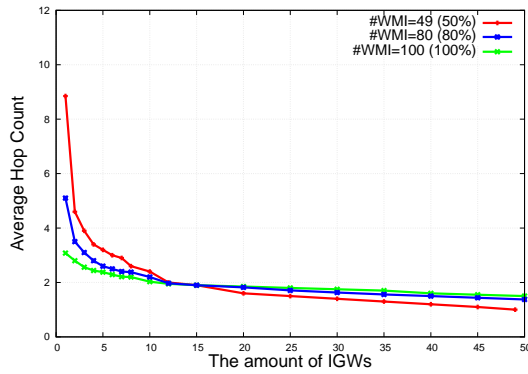


Figure 4.10: Average hop count (information delay) v.s. the amount of deployed IGWs (cost) under the best (100%), the average (80%) and the worst (50%) cases for sensor lifetime in map 1

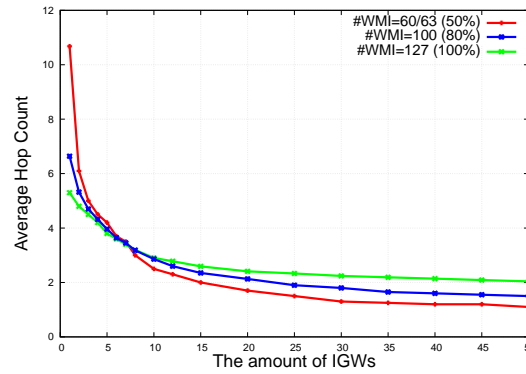


Figure 4.11: Average hop count (information delay) v.s. the amount of deployed IGWs (cost) under the best (100%), the average (80%) and the worst (50%) cases for sensor lifetime in map 2

sensor's lifetime correlates to the amount of intersections based on the characteristics of maps.

4.4.4 Cost of infrastructure

The cost of infrastructure is calculated by $\$MR \cdot \#MR + \$IGW \cdot \#IGW$, where $\#WMI = \#MR + \#IGW$ and $\$IGW > \MR ($\#$:amount, $\$$:price). Both Fig. 4.8 and 4.9 show the relationship between the cost and the delay with the minimum amount of WMIs ($\sim 50\%$). The IGW deployment can be seen as a cluster problem on parking sensors' geographical position. According to the amount of IGWs, we divide all the WMIs into several partitions and then select one IGW from each of them. In Fig. 4.8, the amount of WMIs in map 1 is fixed to 49 even there is only one IGW. That is because each WMI is interconnected thanks to the grid-like topology. On the contrary, in Fig. 4.9, the additional WMIs are required in map 2 when there are less than four IGWs. That is

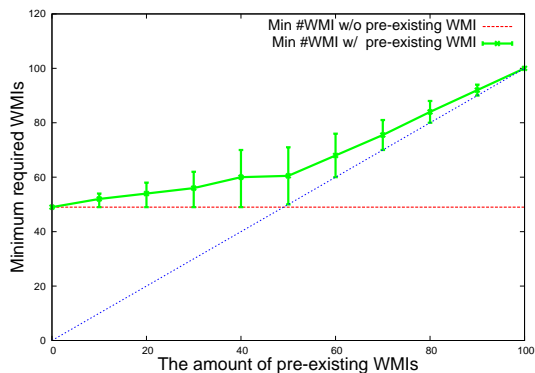


Figure 4.12: The total amount of required WMIs (total cost) v.s. the amount of pre-existing WMI in map 1. The difference between the green and blue curves is the cost of the extra WMIs (extra cost).

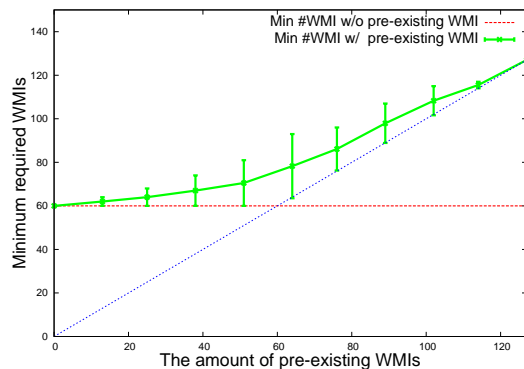


Figure 4.13: The total amount of required WMIs (total cost) v.s. the amount of pre-existing WMI in map 2. The difference between the green and blue curves is the cost of the extra WMIs (extra cost).

because those wireless links between the 60 WMIs form 4 clusters geographically. When we select one IGW in map 2, these 4 clusters require extra WMIs to be interconnected. Thus, if we want to install IGW without creating any additional wireless radio links in map 2, the minimum IGW amount will be four.

4.4.5 Information delay

From our previous work [86], the information delay is proportional to the hop count and the sleep-wake scheduling, i.e., duty cycle. To prevent packet collision caused by channel interference, each hop takes at least one duty cycle. Since the network traffic is quite scattered in most urban sensor networks, the generated packets are often sent within one duty cycle. The information delay can then be calculated by the product of hop count and the duration of duty cycle. In Fig. 4.7, we see that the amount of WMIs impacts the energy consumption. Thus, we take three different amounts to stand for the worst (50% of intersections), the average (80%) and the best (100%) cases of the sensor's lifetime, respectively. Fig. 4.10 and 4.11 show the relationship between the hop count and the amount of IGWs, i.e., the trade-off between the cost of infrastructure and the information delay under different situations of sensor's lifetime. When the amount of IGWs is low, increasing the amount of WMIs helps to reduce the information delay; however it does not apply the other way around.

4.4.6 Integration of pre-existing mesh networks

Mobile network operators (MNO) often take advantage of domestic WiFi hotspots to expand their public WiFi service. These hotspots could also be used as WMIs in wireless urban sensor networks via a plug-and-play zigbee network adapter or an extended network of 802.11 family, e.g., 802.11s. Thus, we define z_i is a binary value which equals to 1 if there is a pre-existing WMI in v_i , so that $x_i \geq z_i \quad \forall i \in V$. We consider a random generated map of pre-existing WMIs $\{z_i\}$. After re-executing our equations on map 1

and 2, the results are shown in Fig. 4.12 and 4.13. The red line is the minimum amount of required WMIs. The blue line is the amount of pre-existing WMIs, i.e., existing hotspots. The difference between the green and blue curves is the extra WMIs we need to install (extra cost). Since the map of pre-existing WMIs is stochastically generated, their position is not optimized. That makes the total amount of WMIs increases but less expensive for the city to start from scratch. Both Fig. 4.12 and 4.13 show two phases in the influence of the pre-existing WMIs. The amount of pre-existing WMIs positively correlates to better deployment. On the other hand, if the pre-existing WMIs are more than half of the intersections, less extra WMIs are required. The existing hotspots can always access the Internet directly and can be seen as IGW. Hence, the extra WMIs are the less costly MRs.

4.5 Summary

In this chapter, we studied and introduced a wireless on-street parking sensor network from the viewpoint of system deployment. We highlighted some important factors and parameterized them in the linear equations. To consider a more realistic urban environment, we retrieved two different parking maps with the same parking area length. We then took their adjacency matrices as our data input and solved them by a multi-objective optimization. We provide our insight and observation based on the results of five types of figures: the characteristics of maps while deploying city mesh infrastructure, the trade-off between sensor's lifetime and cost of infrastructure, the trade-off between information delay and cost of infrastructure at the minimum cost (minimum amount of WMIs), the relationship between sensor's lifetime, information delay and cost of infrastructure, and the additional cost of integrating into the pre-existing infrastructure. While deploying city mesh infrastructure, our model can give a clear sketch so as to anticipate the minimum cost of city infrastructure with an expectable network performance.

The traffic intensity is not considered in the results because the packet generation rate is quite low. However, if we transform the model to an heterogeneous urban network, the traffic intensity will be an issue, and the aggregation problem will have to be considered. Since the metropolitan sensor network attracts more and more attention to urban service, the IGW can also play the rule of the road side units. This way, the buffer size and the vehicle trace will have to be considered in the equations later.

Part III

Urban Service: A Distributed Service for Smart Parking Assistance

An Extended Content-based Publish-Subscribe Service

5.1 Introduction

Thanks to the rapid growth of M2M technology, cities are ready for deploying urban services. Smart parking has been one of the first implemented urban services in smart cities. Smart parking apps have mushroomed all over the world. Current smart parking apps usually provide a graphical user interface for drivers to choose their preferred parking places. However, parking information is dynamically changing and it is always forbidden to operate smartphone while being at the wheel.

For this reason, publish-subscribe service is proposed as the most favorable event messaging paradigm for urban services. Publish-Subscribe service is designed for users who are interested in various spatio-temporal information, especially in urban areas. Users have to first describe their interests as an information subscriber. Certain APIs, such as *subscribe()*, *subscribe_update()* and *unsubscribe()*, can assist users to specify their interests. In relative terms, the information source is the publisher that spreads the information it possesses to network using *publish()* without knowing who are its subscribers. In order to conduct the information to the correct subscribers, intermediate network nodes have to read the message content and execute an interest-data matching. If a specific server exists to cope with these subscription and publication messages, we name it *broker*. Broker maintains a subscription list and a publication table, and then performs *notify()* when there is a new subscription or a new or updated publication. To notify all the interested subscribers of a new or updated publication at once, a multicast or multi-geocast routing of underlying network is required instead of consistent transmission.

Such a Publish-Subscribe event messaging paradigm is an application-level network since the information flow is driven by the users' their interests and geo-locations. As a result, the network path between publisher and subscriber can be long according brokers' behaviors. Smart municipal parking service usually adopts parking sensors as information source. Sensors publish their occupancy status to closest gateway, namely roadside infrastructure (RSI) or infostation, if there is any change. Parking detection sensors are generally deployed in metropolitan road networks and restricted to the urban street layout, so do drivers and the corresponding RSIs. The available parking information is collected by RSIs from on-street sensors, and then appeared on drivers' devices, i.e., smart parking apps on smartphones, peer-to-peer (P2P)

network infrastructure. If RSIs and vehicles communicate through mobile network, RSIs or a central server can be the brokers. If cruising vehicles get information from opportunistically vehicular network (V2V and V2I), vehicles and RSIs can both be the brokers and form a structured overlay. This way, each vehicle has a public buffer to store shared information and private ones for personal use.

However, many ensuing problems are provoked in such a service system, for example, the annoying endless parking search conflicts. This is resulted from the lacks of user's service consideration and the scalability of service deployment. The former shall adapt the network behaviors to the users' context [238] and message content. The latter shall permit the storage and propagation of information to be done efficiently in a dynamically changing urban environment. Centralized cloud-based system is universally known for its scalability [239; 240], however, it requires a costly seamless network connection between RSIs in order to provide the one-hop look-up technique. Contrarily, opportunistic P2P-based network, which omits the physical cable installation, seems to be an alternative solution in metropolitan areas [241–243].

In this chapter, we propose a messaging paradigm named SCAMP (Service -centric Continuous Announcement Messaging Paradigm) to dispose thoughtfully urban information. Considering the already achieved optima of the existing centralized solutions, we postulate that SCAMP is deployed in fully opportunistic vehicular networks, so that information will travel between cars (V2V) and RSIs (V2I). To solve the parking conflict problem, we adopt a continuous update service within SCAMP to disseminate the real-time parking information, that is, an extended Publish-Subscribe messaging paradigm. Publish-Subscribe service allows drivers to specify and subscribe to information which they are interested in and then to receive a *push* if there is any update. Sets of publications and subscriptions have to be maintained distributedly and dynamically. All vehicles and RSIs can perform an interest-data matching in order to steer the new or updated publications to correct subscribers and vice versa. Since RSI is always fixed and manages sensed information directly from sensors, it plays consistently the role of brokers and forms a structured overlay which allows information to be accessed more efficiently.

As such, opportunistic network relies on vehicles to carry, forward or reply to all messages. Three key points will affect vehicular behaviors in SCAMP: if vehicles consider themselves a proper node to forward/reply to messages for others according to their location and mobility, if messages are worth being forwarded/replied to in terms of the matching results, and if vehicles have incentives to forward/reply to messages. The chapter has the following two main contributions: First, we propose a partial crowd-sourcing continuous update parking service supported by mobile vehicles and roadside infrastructure at junctions. Vehicles and RSI are fully opportunistic without installing any costly cables. Second, we adopt a Publish-Subscribe messaging paradigm to provide continuous update services for mobile users by using key-based routing protocols in a structured manner. The content matching can result in 8 different actions: to forward or not, to respond or not, to make a new query or not, and to respond according to the

new query or not.

5.2 Related works

Publish-Subscribe

As previously mentioned, Publish-Subscribe is an information-centric service. While deploying Publish-Subscribe in a fully opportunistical network, the consideration of user's context and message content is the most significant. In the emerging opportunistic network, user's mobility is the main concern. Fotiou *et al.* [244] presented a Publish-Subscribe architecture Ψ supported by the built-in multicast and caching mechanism. Ψ is an information-centric model which can support mobility. Authors compared their solution with traditional internet mobility ones to show the advantages of Ψ .

Rezende *et al.* [245] presented a Publish-Subscribe communication in mobile ad hoc network and showed the impact of mobility in shaping the network behavior. To extend publisher's and subscriber's communication range, different mobile nodes can be used as brokers. T. Pandey *et al.* [246] proposed a Publish-Subscribe communication in vehicular network. Since brokers always play the most important roles to couple and decouple publishers and subscribers, authors presented a structured P2P overlay of mobile brokers using city buses. Because of the unstable connectivity between mobile brokers, message aggregation is often applied in order to maximize the information quantity per transmission.

N.K. Pandey *et al.* [247] proposed a distributed approach to Publish-Subscribe aggregation. Authors presented 3 different aggregation methods: early at the publisher's edge, late at the subscriber's edge and adaptive rate-based at the brokers' edge. The early aggregation significantly reduces the traffic for workloads where the publication rate is higher than the aggregation notification rate. But this approach is not always optimal. The adaptive rate-based method can help improve under some situations. The service type is crucial to the description of user's interest, namely message content. Since each node has to match the set of publications with that of subscription and vice versa, it will have to make decision based on matching results. However, messages are forwarded or/and replied by one vehicle or RSI according to information quality. If the information is very useful for subscriber, vehicles shall be in support of replying this message. Otherwise, vehicles shall favor to forward this message to get more complete matching results. Hyytiä *et al.* [248] define a 4-action set to assess the most appropriate decision to make after doing a content matching.

Tariq *et al.* [249] proposed a P2P-based Publish-Subscribe system with subscriber-defined QoS. Subscribers adjust the granularity of their subscriptions according to their bandwidth constraints and delay requirements in a decentralized manner. If subscriber's interest is not well defined, the Publish-Subscribe system can only execute a bad matching and reply nothing to subscriber. Thus, subscription adaption is needed to compensate

for the availability of data. Jayaram *et al.* [250] proposed an algorithm to adapt subscription without hampering throughput or latency. Sermpezis *et al.* [251] studied the relationship between content's popularity (interest) and availability (data). They established an analytical framework to see the effects of these factors on the delay and success probability of the service access through opportunistic network.

Geocast

Geocast is to send messages to a certain geographic area. It is a challenge to implement a geocast in opportunistic network since we cannot guarantee that messages always arrive where we want to send. Most data dissemination solutions tried to flood directionally the network and increased the packet reception rate [252]. However, flooding causes too many packet collisions due to the hidden terminal problem in urban areas, so that it drops the network throughput and successful transmission rate. To avoid this problem, vehicles shall decide who forwards their receipt messages based on several retransmission heuristics. Hall [253] presented two primary heuristics: minimum transmission time and distance threshold, which take the amount of heard copies in the medium and the distance from message transmitters into account. Forwarding alone cannot always take messages far. Some other factors shall also be considered, such as heading direction and location, to decide if vehicles can carry messages to specific areas in case of no pathway to transmit. Ahnn *et al.* [241] designed a scalable sensor network platform to share location-aware information called GeoServ. Mobile users can publish or access sensor data via distributed P2P overlay network. A geographic map id from Tigermap gives a GID (grid id) to the sensed data in each grid area. While users send an information query, the geocast routing can find data location via its GID.

5.3 Publish-Subscribe architecture

Fig. 5.1 shows an illustration of three-layered system architecture. Content layer contains two kinds of information: *users' interests* and *parking data*. Users' interests stand for subscriptions (in green) and sensed parking data are the publications (in blue). In most cases, drivers know that the parking information is around their destination. Infrastructure layer shows the physical network in the real world. The data travel between vehicles and RSIs according to users' interests. Since RSI is always fixed at junctions, there is a minimum distance between any two adjacent RSIs, and RSI often has a higher network degree than vehicles. Hence, we designate these still RSIs to be cluster heads who manage the mobility of information subscribers by sending the mobility updates (in orange). Each cluster is a quadtree naming region. When one publisher in the cluster 1100 publishes an update to the network, each node verifies first if the receipt message matches up their own interests. If so, the node receives this message and forwards it if there is any subscribers around. Otherwise, nodes check their own driving direction to see if this message can hitch a ride. The message forwarding follows the content-based and geocast addressing in the logical layer. That is to say, the information will be delivered to its local subscribers and where there are distant information subscribers with cluster heads' addresses namely the quadtree GID. The system design will respect the follow-

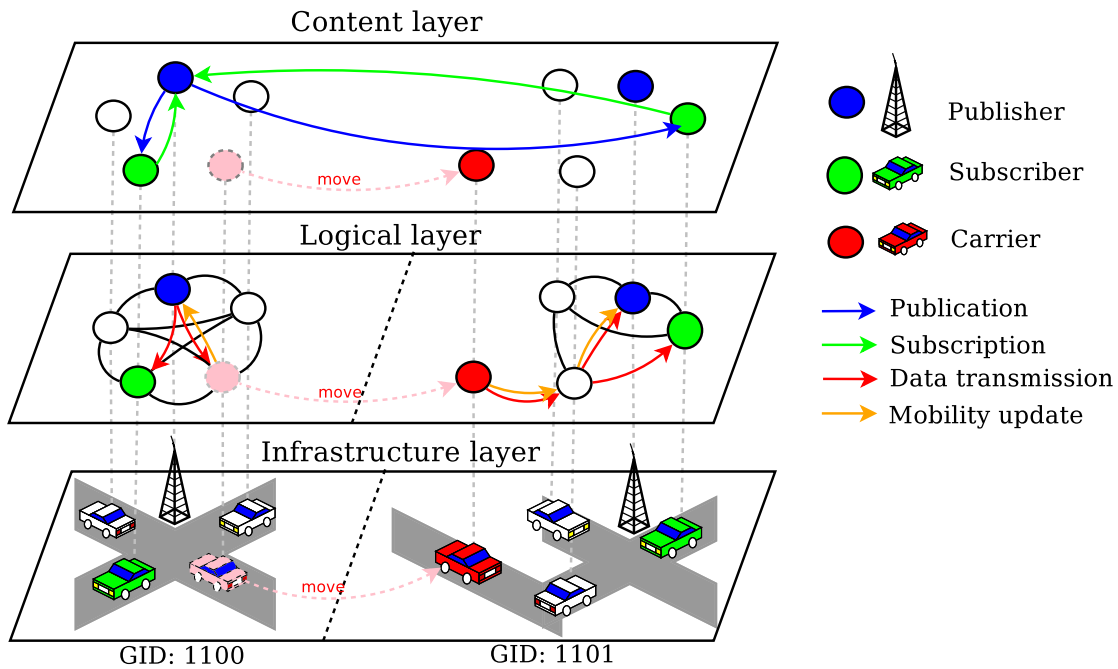


Figure 5.1: Illustration of SCAMP's three-layered system architecture

ing requirements: First, drivers can access the geographic parking information without interruption by using continuous update service. Second, the system shall be always aware of user's latest location in order to provide the required information continuously as fast as possible. Finally, since the parking availability changes dynamically according to the vehicle flow, so does the network. Thus, the message aggregation, splitting and customization shall be taken into account.

5.3.1 Publish-Subscribe service

Fig. 5.2 shows that publisher and subscriber-ends are realized in the application layer, however, Publish-Subscribe service is mainly supported in the logical layer. The logical layer grants the system intelligence to be able to deal with events and guarantee the seamless message exchange between content and infrastructure layers. When publishers or subscribers send messages containing publications or subscriptions to the network, the logical layer has to match them up and then steer messages to correct destinations. It means a broker is implemented in intermediate nodes in order to maintain the sets of publications and subscriptions and to execute the interest-data matching. Then intermediate nodes will decide how to process the messages according to matching results and some piggybacked information. Once subscribers receive the interesting information, they may change their mind on which impacts the information dissemination geographically.

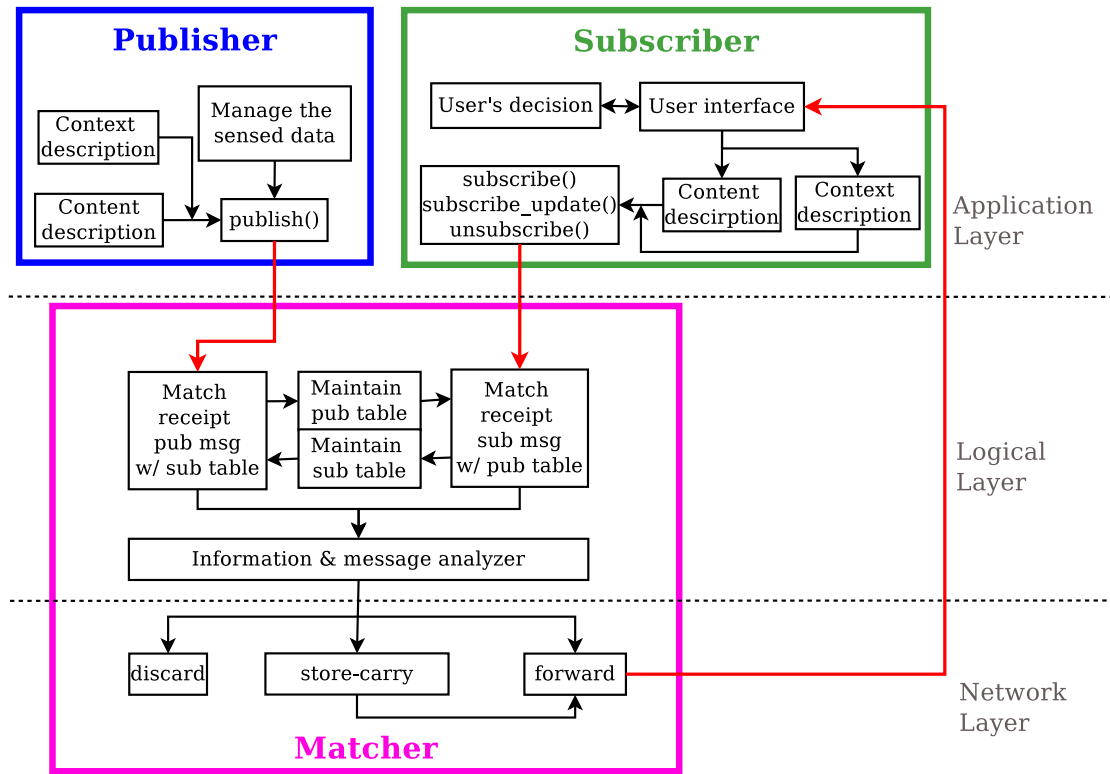


Figure 5.2: Publish-Subscribe service architecture

uid = 1817	rid = 578973
gid = 1100	$t_{stamp} = 20140703T11:15$
$s_{type} = \text{'parking'}$	$G_S = \begin{cases} \langle n_{park} \rangle_m \\ \langle \mu, \sigma^2, n_{gap} \rangle_{um} \end{cases}$
$p_{type} = \text{'standard'}$	$N_D = 1$
$v_{type} = \text{'Nissan xxx'}$	$N_E = 3$
$dst = \langle lat, lon \rangle$	$cost_S = \text{€1/hr}$
range = 400 m	$cost_E = \text{€2/hr}$
$t_{park} = 20140703T13:05$	$R_e = 15\%$
$f_M = \langle \alpha, d \rangle$	

Figure 5.3: An example of driver's subscription (left) and RSI's publication (right).

5.3.2 Driver's interest

Vehicular drivers can subscribe, unsubscribe and update their subscription of parking information simply by specifying their interests in the subscription. Fig. 5.3 gives an example of interest description of one driver. To identify each driver and his/her location, the content includes the driver's id and geolocation. Drivers shall also specify their vehicle type in case of non-demarcated parking areas. Besides, drivers shall provide the estimated parking time to classify the message priority. The historical information is neglected since future drivers are not involved in the parking game. $range$ and f_M are used by the broker for executing matching and information quality analysis. Let C_{uid}

denote the set of drivers' interests:

$$C_{uid} = \{c_{uid}(t) | t \in T\} \quad (5.1)$$

$$c_{uid}(t_{park}) : \langle uid, gid, s_{type}, p_{type}, v_{type}, \langle lat, lon \rangle_{dst}, range, t_{park}, f_M \rangle \quad (5.2)$$

5.3.3 Parking availability information

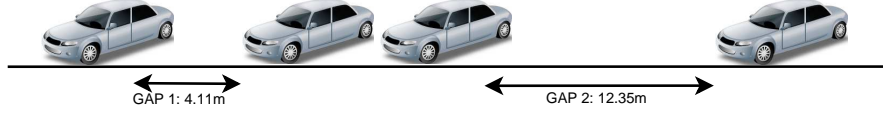


Figure 5.4: Illustration of a on-street parking segment with two gaps

The on-street parking zones in France are mostly non-demarcated. To collect the information from non-demarcated zone, we first assume that sensing technology is good enough to provide multiple detection with the length of available parking spaces (Fig. 5.4). For each road segment with on-street parking, the available parking information is the amount of gaps between two adjacent parked vehicles and their corresponding lengths. For example, the vehicle length varies from 2.5 to 4.17 meters in France. A gap of 3.5 meters is only interesting for the vehicles less than 3 meters. If a driver is querying the parking occupancy information within certain time or certain distance, it implies that this driver is very close to the destination and only interested in the accurate information. Then a list of road segments which conforms to this driver's interests will be sent to this driver. Otherwise, a list of road segments with the historical statistics from which conforms to the driver's interests shall be provided. This is not considered in our models. We postulate a parking area mixed with demarcated and non-demarcated parking spaces. We presume that the parking information is aggregated from sensors, then the current (r_{ab}) information of each road segment between junctions i_a and i_b is expressed as:

$$r_{ab}(t) : \langle rid, t_{stamp}, G_S, N_D, N_E, cost_S, cost_E, R_e \rangle . \quad (5.3)$$

rid is the road segment id. G_S , N_D and N_E stand for the amount of available standard, disabled and electric vehicle parking, respectively. $cost_S$ and $cost_E$ are the parking fee for standard and electric vehicle parking. R_e is the information error rate which expresses the uncertainty of data and is generally calculated by sensing accuracy, wireless link quality and software/hardware defects. Fig. 5.3 shows an example of parking content description namely publication. A set of publications containing parking contents of several roads is maintained in brokers in order to reply drivers' inquiries. The historical information in $r_{ab}^H(t)$ can be calculated as below and stored in brokers in order to provide users with the predicated occupancy status:

$$G_{t_h}^C = \frac{1}{\Delta T} \int_{t_h} G(\tau) d\tau \quad \text{for } t_h \in T^c \quad (5.4)$$

$$G_{t_h}^H(t) = E[G_{t_h}^C] \quad \text{for } h = 0, 1, \dots, m-1 \quad (5.5)$$

5.3.4 Content-based matching

There are several ways to filter the information issued by publishers. Two main message filterings are topic-based and content-based. Topic-based system allows publishers to title the information by certain topics. Subscribers receive all the information issued by the topics to which they subscribe. Content-based system provides a deeper information filtering, for example, user's location and timestamp. Subscribers receive the information which tallies with their interests. Since subscribers usually do not have knowledge of what kind of information they can subscribe to, the attributes of users' interests are defined in Section 5.3.2. To execute a content-based filtering, we simply see if r_{ab} conforms to user's interest $c_{uid}(t_{park})$.

5.4 Publish-Subscribe on dynamic changing network

5.4.1 Information aggregation

Since parking sensor is usually individually installed, the information received is also discrete. While drivers are looking for parking places, they only want to know if there is at least one parking place on a street no matter where the place is exactly. Also, the availability of non-demarcated street parking is somehow difficult to be presented separately. Thus, an early information aggregation is performed on RSIs, so that drivers can see the occupancy status of each street, shown in Fig. 5.3. While executing a content-based matching, brokers will verify all the publications or subscriptions in their buffer. If there is a new or updated subscription, all the suitable r_{ab} will be aggregated into one message and be delivered to the subscriber. If there is a new or updated publication, all the $c_{uid}(t_{park})$ tallied with it will be notified through multiple geocast.

5.4.2 Key-based geocast

The vehicle mobility increases the packet loss rate but also provide an opportunity for a message to go farther. Messages can be carried and forwarded within an uncertain delay time according to vehicular heading direction and speed. SCAMP adopts a key-based routing which uses the geographic location as the key space. We assume that each RSI and vehicle have map data associated with grid references. If the grid size is $R \times R$ in a $X \times Y$ regions, we need at least $2^Z (\geq \frac{X}{R} \times \frac{Y}{R})$ grids to cover the whole region where Z is the smallest exponent. Each grid contains at least one RSI and nodes in the same grid generally shares the same information. When a driver sends a demand of a querying area, we verify the grid id of the destination and send this message there. On the other hand, the publication will be sent upon the subscription table from its neighborhood grids, i.e., greedy routing using neighborhoods instead of exact neighbors. That is to say, each node only knows if its neighbors are interested in its publications via multicast geocast (store-carry and then forward) and if there is any interested local subscriber via multicast (forward directly).

Algorithm 1: PubSub algorithm: Publication and subscription table maintenance

```

Input: PACKET
Output: QUERY, RESPONSE
Data: publicationTable, subscriptionTable, InputQueue
Result: publicationList, subscriberList, Action
1 initialization;
2 while receive message PACKET do
3   switch type of PACKET do
4     case publication/notification
5       if new then
6         update publicationTable;
7         match PACKET with subscriptionTable;
8         if obtain subscriberList then
9           | put publication of PACKET into publicationList;
10        if dst of PACKET is localhost then
11          | receive(PACKET);
12     case subscription/subscription update
13       if new then
14         update subscriptionTable;
15         match PACKET with publicationTable;
16         if obtain publicationList then
17           | update  $f_M$ ;
18           | put sender of PACKET into subscriberList;
19         Action =  $\max\{a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8\}$ ;
20         if Action =  $a_1$  or  $a_4$  then
21           | PACKET =  $\phi$ ;
22         if Action =  $a_2, a_3, a_5$  or  $a_6$  then
23           | modify PACKET;
24         if Action =  $a_1, a_2$  or  $a_7$  then
25           | publicationList =  $\phi$ ;
26           | subscriberList =  $\phi$ ;
27         if Action =  $a_3$  or  $a_6$  then
28           | match PACKET with publicationTable;
29           | if obtain publicationList then
30             | update  $f_M$ ;
31             | put sender of PACKET into subscriberList;
32     case Unsubscription
33       | update subscriptionTable;
34   if publicationList  $\neq \phi$  and subscriberList  $\neq \phi$  then
35     | put publicationList into data of RESPONSE;
36     | put subscriberList into receiver of RESPONSE;
37     | Insert RESPONSE into InputQueue;
38   if PACKET  $\neq \phi$  then
39     | let QUERY = PACKET;
40     | insert QUERY into InputQueue;

```

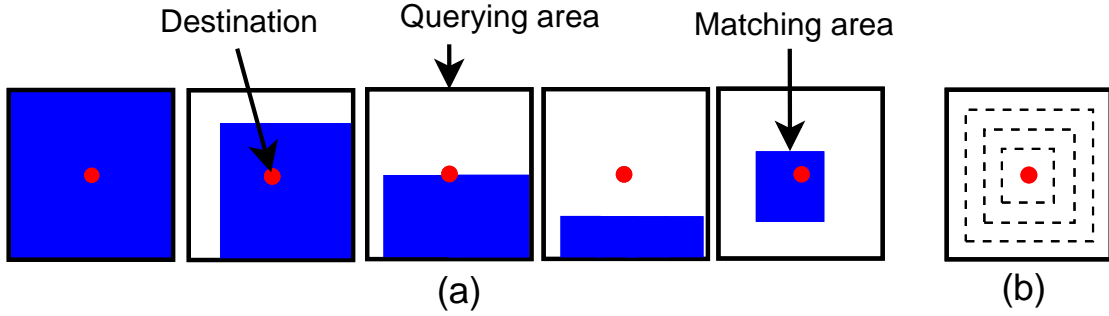


Figure 5.5: (a) Examples of matching results (b) Spatial partitions of a querying area to evaluate if the matching result is good

Action sets	Actions			
	FW	RE	NQR	NRE
$a_1 = I(d) + U(d) - 2\alpha$	x	x	x	x
$a_2 = I(d) + U(b) - 2\alpha + e$	x	x	o	x
$a_3 = I(d) + U(b') - (2\alpha + \beta - e)$	x	x	o	o
$a_4 = I(b) + U(d) - (2\alpha + \beta - e)$	x	o	x	x
$a_5 = I(b) + U(b) - (2\alpha + \beta - e)$	x	o	o	x
$a_6 = I(b) + U(b') - (2\alpha + 2\beta - e)$	x	o	o	o
$a_7 = I(b) - (\alpha' + 1) + (1 - F(d_{matcher-dst}))$	o	x	x	x
$a_8 = 2 \cdot I(b) - (\alpha' + \beta + 1 - e) + (1 - F(d_{matcher-dst}))$	o	o	x	x

Table 5.1: Action set to decide if a message shall be forwarded (FW), responded (RE), modified to a new query (NQR) or responded according to the new query (NRE).

5.4.3 Quality of information

First, SCAMP has to maintain the publication and subscription tables wherever subscribers are. Good publication and subscription tables result in a good interest-data matching without dropping the service performance by useless messages. However, the user's query does not always have to arrive the geocast region in order to get responses. If the querying area is popular, some intermediate grids probably have the wanted information. If so, it can avoid unnecessary retransmissions to reduce the information delay. Thus, the goal of content matching is to provide a good response along the network route.

In each matching, the matcher will have to know if the matching result is complete and if there is useful information for drivers. Fig. 5.5(a) shows some examples of matching results. If the matching area in blue is nearly equal to the querying area, we consider that the matching is good and the matcher does not have to forward this query. Otherwise, the matcher will check the spatial distribution by indicating the percentage of the matching portions in the different partitions in Fig. 5.5(b). Afterward, the matcher will compare and modify f_M mentioned in Section 5.3.2 to know whether it has to forward or response this query. We let $f_M = \langle \eta, I(d), U(d) \rangle$ denote the search state when the query arrives a matcher, where η is the travelled hop number; d is the

highest valued matching that is already done by preceding nodes. b is the highest valued matching that this matcher could send and e is the cost of each transmission. $I(\cdot)$ is the entropy of information and can be expressed as $\sum_i dist(r_i, dst)^{-1}$. $dist(\cdot, \cdot)$ is the distance between any two given locations. $U(\cdot)$ calculates the usefulness of information. Here, $I(\cdot)$ considers only the availability of information, on the contrary, $U(\cdot)$ verifies if information is useful for drivers.

We take the definition of the action set $\{a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8\}$ by extending from [248]. The best action will be chosen according to $w(\alpha, \beta, d, b) = \max\{a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8\}$. In which, $a_1, a_2, a_3, a_4, a_5, a_6, a_7$ and a_8 are calculated respectively by the equations in Table 5.1. They are to forward, respond, make a new query or respond upon the new query will depend on the results of these eight variables. α stands for the completed percentage of the trajectory, it can be expressed as $\alpha = (\eta \cdot d_{hop}) / (\eta \cdot d_{hop} + dist(matcher, dst))$. β is the percentage of the trajectory to reply a message, it can be expressed as $\beta = (dist(src(gid), dst)) / (\eta \cdot d_{hop} + dist(matcher, dst))$. α' is next hop of α and can be expressed as $\alpha' = ((\eta + 1) \cdot d_{hop}) / (\eta \cdot d_{hop} + dist(matcher, dst))$. d_{hop} is the ratio to convert the hop number to distance. $F(\cdot)$ is the CDF of information distribution, giving the probability of getting a better response with respect to the distance between message's current location and the destination.

Lines 12-31 in Algorithm 1 shows the content matching of one subscription with multiple publications. With the arrivals of subscriptions, the subscription table is built gradually. When there is an information update, nodes will compare the publication with their subscription tables in order to send notifications, shown in lines 4-11 in Algorithm 1. If there are more than two subscribers to notify, a multi-cast will be performed. That is, a response will be sent if the matching results are not empty (lines 34-37), and the message can be forwarded according to the matching (lines 34-40).

5.4.4 Mobility impact to the maintenance of publication and subscription table

Since nodes have their map data and know which grids they are and which grids they are going to. As in Algorithm 2, vehicles check up the input queue to know if they have packets to send in the departure or arrival grids. If there are, vehicles will include their updated grid id within the aggregated messages in order to insert or delete their own subscriptions, i.e., vehicles themselves are the best candidates to maintain their own subscriptions. The user's mobility information can be expressed in the subscription update. If vehicles have messages to send, they will verify if this message is for the local grid (lines 9-10), calculate if the distance from the sender is far enough (lines 7-8) and check if they did not hear any copy (lines 5-6). If so, the message will be retransmitted in the grid until it arrives to the correct receivers. If the message is for the neighbor grid(s), vehicles will (lines 12-15) check their own heading direction to decide if they store and carry this message themselves. When messages are in the output queue, messages for the same destination will be aggregated (lines 10 & 15) in order to reduce the transmission times.

Algorithm 2: Geocast algorithm: Forward, store-carry, or discard

Data: INPUTQUEUE, OUTPUTQUEUE
Result: MSG, MSG_L

```

1 initialization;
2 if leaving or joining a grid then
3   for  $i := 1$  to QueueSize do
4     take a MSG from INPUTQUEUE;
5     if hearing a copy of MSG then
6       └ discard MSG;
7     if src of MSG ( $\neq$  localhost and  $\leq D$ ) then
8       └ discard MSG;
9     if dst of MSG = local grid then
10      └ MSGL += MSG;
11    else
12      if heading the same direction as MSG then
13        └ insert MSG back to InputQueue;
14      else
15        └ MSGL += MSG;
16    └ MSG =  $\phi$ ;
17  if MSGL  $\neq \phi$  then
18    └ insert MSGL into OutputQueue;

```

Type	Vehicular Network	Cellular Network
Models		
Mobility	Parking, driving(0-15 m/s), roaming(5-20 m/s). Granularity: 1s	
Pathloss	Corner + Rayleigh fading	Okumura-Hata
Radio	10Mbps	3.6 Mbps
Tx Power	RSI/Vehicle: 23 dBm	RSI/Vehicle: 23 dBm, BTS: 43 dBm
Rx Sensitivity	RSI/Vehicle: -105 dBm	RSI/Vehicle: -117 dBm, BTS: -121 dBm
Antenna Height	RSI: 1.5m, Vehicle: 0m	RSI: 1.5m, Vehicle: 0m, BTS: 25m
MAC	Contention-based Carrier sense	Schedule-based
Routing	Multi-geocast	Layer 3
BTS Density	-	1 BTS/km ²
App & Logical	SCAMP, Publish-Subscribe	Publish-Subscribe
Simulation Time	20000 seconds	
Simulation Area	1.2×1.2km ² , 3×3km ²	
	Intersection distance: 120m, road width: 20m	
Parking Time	Weibull (α_p, λ_p); $\alpha_p = 0.5, \lambda_p = 600$	
Roaming Time	Weibull (α_r, λ_r); $\alpha_r = 1, \lambda_r = 5$	
Grid Length	200,300,400,600,720,960,1000,....	
RSI Density	1 RSI per grid	

Table 5.2: Simulation Parameters for vehicular network and mobile network

5.5 Evaluation

To test our model, we construct our simulation environments in three different kinds of scenarios with the corresponding parameters in Table 5.2. Then perform them with the WSNET simulator [228]: First, we verify different combinations of e and d_{hop} to select the most suitable parameters. Second, we change different grid sizes while applying geocast for spreading information. Third, we evaluate how the amount of users impacts the network performance. Fourth, we show the comparison between mobile and vehicular networks.

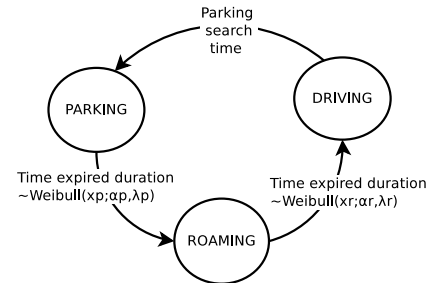


Figure 5.6: Mobility model

5.5.1 Modeling vehicle mobility

Since the network traffic correlates closely with drivers' behaviors, we define three different driver's states, shown in Fig. 5.6. Driving state means that a driver has set a destination and steers to it. When a driver switch to this state, he will send an inquiry describing his parking interests (subscription) in order to get the parking information around his destination. Drivers can also update their interests (subscription update) while moving around the city. Once the driver finds a parking place, he will switch to the parking state, send a message to terminate his subscription (unsubscription), and park for a while, i.e., parking time. When the driver finishes parking and starts to be active again, he changes to the roaming state and cruises in city with manhattan mobility.

5.5.2 Parametrization

First of all, we explain the parameters e and d_{hop} introduced in Section 5.4.3. The relationship between generated packets, e and d_{hop} is shown in Figs. 5.7 and 5.8 in different sizes of urban areas. Both of them are simulated while the amount of vehicles is half of available parking places (maximum 50% occupancy rate) and nine grids. The impact of d_{hop} and e is quite obvious. Both of them show that the larger d_{hop} and e generates more transmissions per subscription, especially while considering a bigger urban area. e is used to increase the response rate. Whatever the queried information is very rare ($e = 1$) or very popular ($e = 0$), the adaptive e can be used to reduce or increase the matched publication. In $1.2 \times 1.2 \text{ km}^2$, the density of vehicles and RSIs is higher. Since most devices own quite a lot of information and almost always give a response, the response index e does not really affect the amount of generated packets. In $3 \times 3 \text{ km}^2$, each network device owns fewer information and might have a lower information quality, thus the response rate e can influence more the transmission times. Figs. 5.9 and 5.10 show the required time of finding a parking place. Figs. 5.11 and 5.12 show the walking distance between the parking places and destinations. The required parking time is complementary to the generated packet transmissions. If more network devices give a response to drivers, drivers can normally find a parking place fast. Walking distance can also be reduced with more packet transmissions because drivers can have more parking

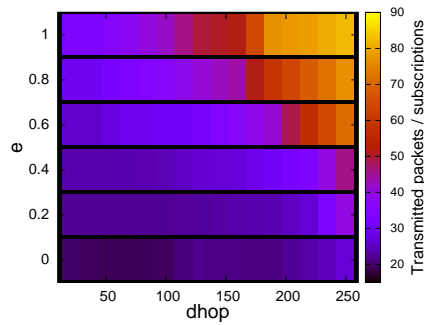


Figure 5.7: SCAMP parameters v.s. the ratio of transmissions to subscriptions in an area of 1.2x1.2 km²

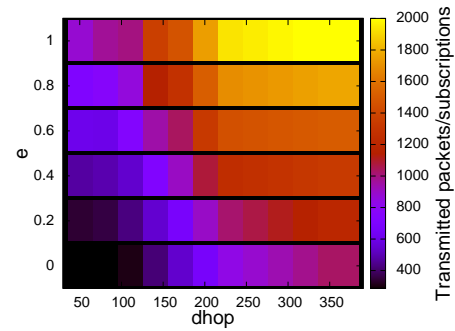


Figure 5.8: SCAMP parameters v.s. the ratio of transmissions to subscriptions in an area of 3.0x3.0 km²

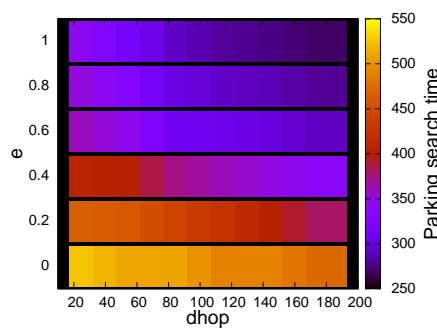


Figure 5.9: SCAMP parameters v.s. parking search time in an area of 1.2x1.2 km²

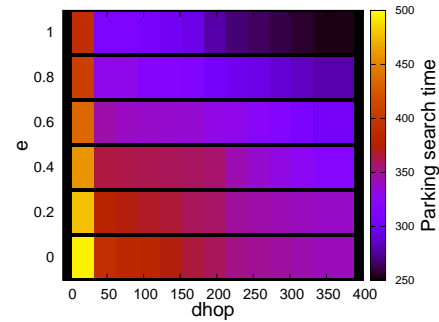


Figure 5.10: SCAMP parameters v.s. parking search time in an area of 3.0x3.0 km²

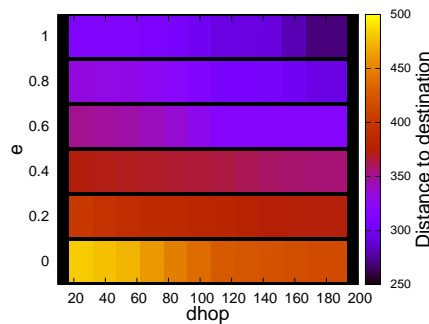


Figure 5.11: SCAMP parameters v.s. parking distance in an area of 1.2x1.2 km²

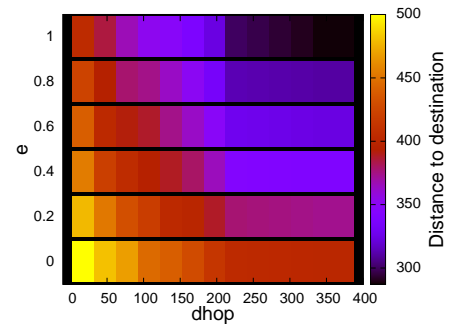


Figure 5.12: SCAMP parameters v.s. parking distance in an area of 3.0x3.0 km²

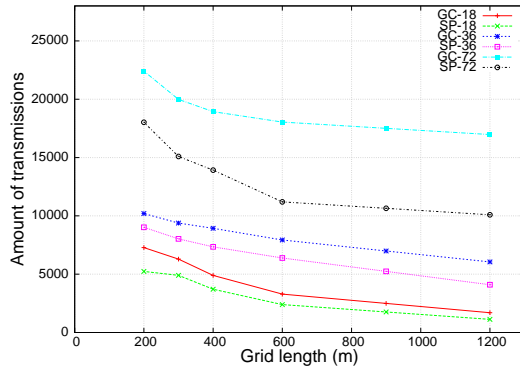


Figure 5.13: Amount of transmissions v.s. grid length with 18, 36, 72 vehicles in an area of $1.2 \times 1.2 \text{ km}^2$

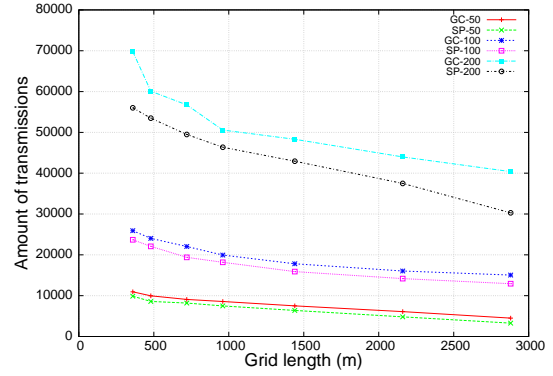


Figure 5.14: Amount of transmissions v.s. grid length with 50, 100, 200 vehicles in an area of $3.0 \times 3.0 \text{ km}^2$

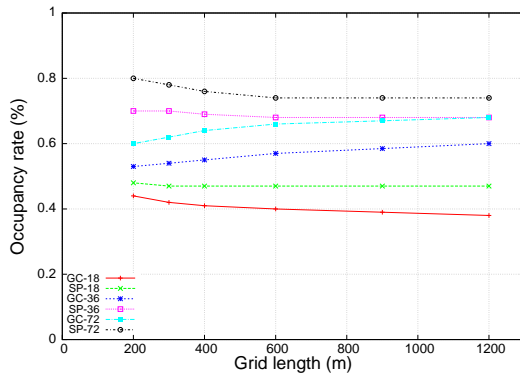


Figure 5.15: Occupancy rate of 36 parking spaces with different grid lengths with 18, 36, 72 vehicles in an area of $1.2 \times 1.2 \text{ km}^2$

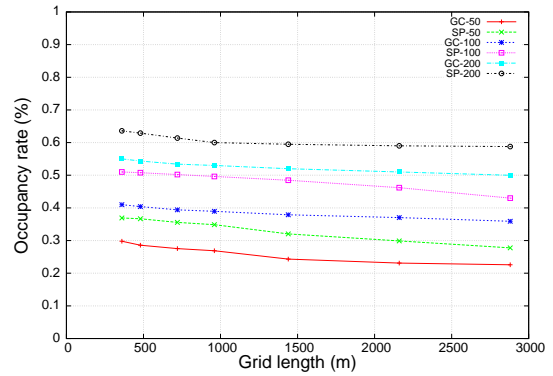


Figure 5.16: Occupancy rate of 100 parking spaces with different grid lengths with 50, 100, 200 vehicles in an area of $3.0 \times 3.0 \text{ km}^2$

choices. That is why d_{hop} and e affects the parking search time and distance. In addition, the parking search time is strongly related to the network delay. To reduce the parking search time and the transmitted packets at the same time, we take $d_{hop} = 120$ and $e = 0.4$. In addition, $F(\cdot)$ is a CDF of exponential distribution with the rate parameter $\lambda = 1$.

5.5.3 Grid size for multi-geocast routing

We assume that each grid size is square and can be expressed as the square of grid length. A pure Publish-Subscribe messaging paradigm is used to compare with our SCAMP model. Here, the pure Publish-Subscribe simply uses the geocast to spread messages without considering the quality of information; thus, we call it Geocast. Three difference scenarios are considered: (1) when parking demand is less than parking supply (18 & 50) (2) when parking demand is equal to parking supply (36 & 100) (3) when parking demand is more than the parking supply (72 & 200).

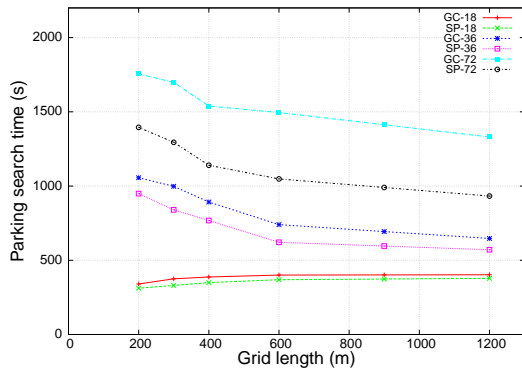


Figure 5.17: Parking search time v.s. grid length with 18, 36, 72 vehicles in an area of $1.2 \times 1.2 \text{ km}^2$

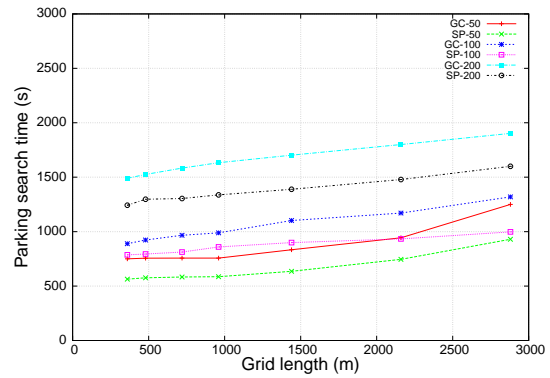


Figure 5.18: Parking search time v.s. grid length with 50, 100, 200 vehicles in an area of $3.0 \times 3.0 \text{ km}^2$

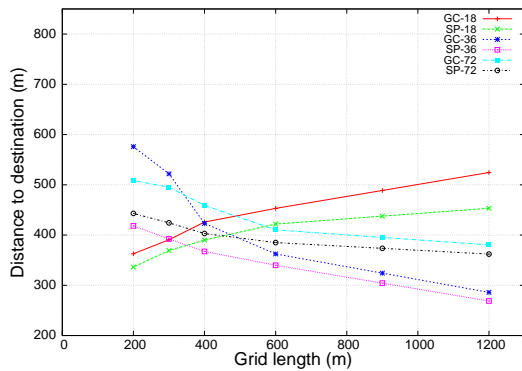


Figure 5.19: Distance to destination v.s. grid length with 18, 36, 72 vehicles in an area of $1.2 \times 1.2 \text{ km}^2$

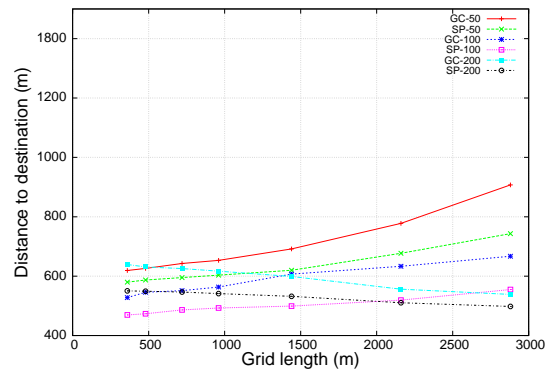


Figure 5.20: Distance to destination v.s. grid length with 50, 100, 200 vehicles in an area of $3.0 \times 3.0 \text{ km}^2$

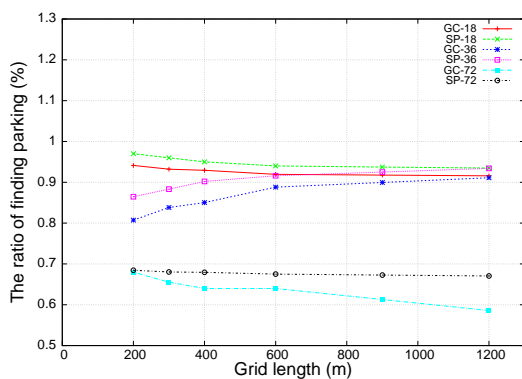


Figure 5.21: Successful ratio of finding parking with 18, 36, 72 vehicles in an area of $1.2 \times 1.2 \text{ km}^2$

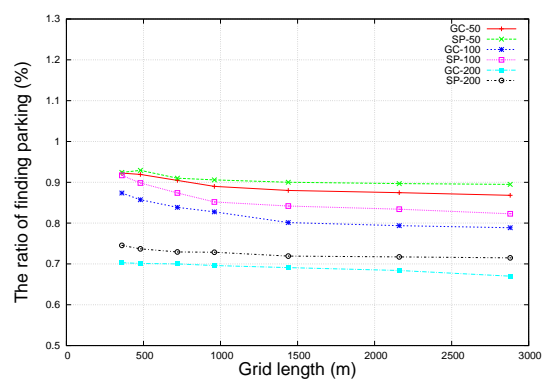


Figure 5.22: Successful ratio of finding parking with 50, 100, 200 vehicles in an area of $3.0 \times 3.0 \text{ km}^2$

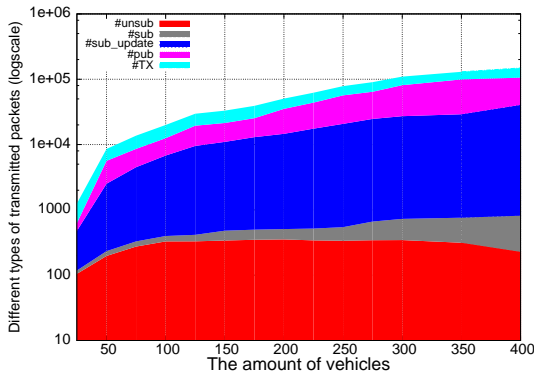


Figure 5.23: Transmitted packets via Geocast in an area of $3 \times 3 \text{ km}^2$

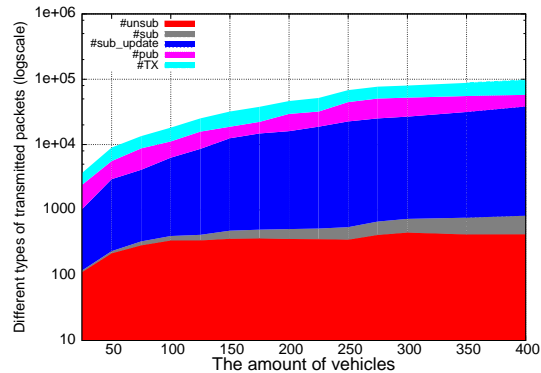


Figure 5.24: Transmitted packets via SCAMP in an area of $3 \times 3 \text{ km}^2$

5.5.3.1 Parking system occupation

First, we look at the grid size from the viewpoint of parking system. The amount of transmissions is inversely proportional to the grid size in $1.2 \times 1.2 \text{ km}^2$ and $3 \times 3 \text{ km}^2$. When the grid size is small, the RSI density is higher and it increases the network traffic. In addition, packets travel more under the condition of small grid. Whatever the grid size, SCAMPE can always achieve fewer transmission times than Geocast, shown in Figs. 5.13 and 5.14. The difference is even more obvious as the increases of vehicle density. However, the system occupation rate is also a bit higher with smaller grid thanks to the denser RSI in $3 \times 3 \text{ km}^2$ (Fig. 5.16). If we shrink the simulation dimension, small grid length can reduce the system occupation rate (Figs. 5.15). That is because there are too many vehicles and RSIs and the channel is too busy to disseminate information.

5.5.3.2 Drivers' satisfaction

Drivers' satisfaction hinges on parking search time, walking distance and successful rate of finding a parking place. From Figs. 5.17, 5.19 and 5.21, we see that the smaller grid size does help to improve smart parking service when the parking demands are less than parking supply. However, as drivers increases, the service drops and drivers can only find a less good parking place with longer search time. When we enlarge the dimension, the parking service performance correlates with grid size, no matter how many drivers, shown in Figs. 5.18, 5.20 and 5.22. The parking distance also reduces when parking demand is more than parking supply in Figs 5.19 and 5.20. That is because less vehicles are parked and those who found a good parking place are calculated. However, SCAMP can always outperform Geocast under all the different situations.

5.5.4 Network and server load

The network load mainly comes from the network packets. If there are generated packets, each machine will have to do the transmissions and receptions. This is costly for the energy and the network capacity. The higher number of generated packets also result in more packet collisions which occupies the channel but sends nothing. In

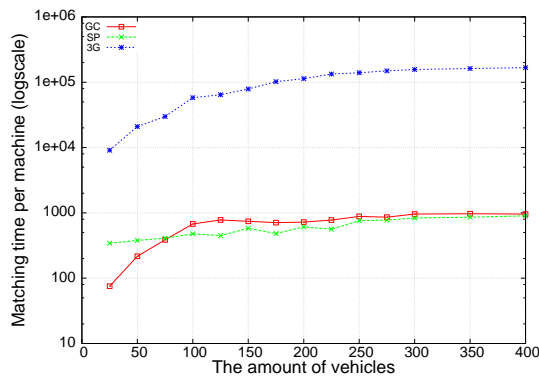


Figure 5.25: Matching times per machine in an area of $3 \times 3 \text{ km}^2$

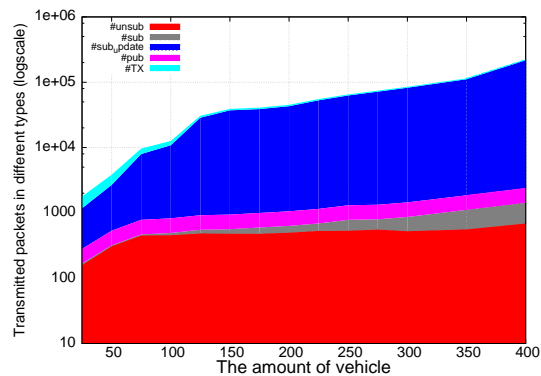


Figure 5.26: Transmitted packets via mobile network in an area of $3 \times 3 \text{ km}^2$

cellular network, the main type of packets are subscription update. Because the cellular network lets all the drivers receive the same parking information and compete the same parking area, most drivers have to go to the current best parking place which might be far from their current locations. Thus, a lot of mobility update messages are generated during the retry period (Fig. 5.26). Geocast and SCAMP are different from cellular network. Since the content matching is done separately or often repeatedly on different machines, there are often too many matched publications. Fig. 5.23 and 5.24 show the different types of transmitted packets via Geocast and SCAMP. Geocast generates more publications than SCAMP because of missing consideration of information quality.

Fig. 5.25 shows the matching times per machine under centralized and opportunistic networks. Centralized method, which processes all demands on a powerful server, is the most common way so far. Opportunistic method allows all vehicles and RSI to participate to the content matching in order to share the maintenance tasks. Thus, each machine (vehicle/RSI) just needs a minimum calculation power to match the interests of its neighborhoods and the data it owns. In addition, SCAMP does not reply to each user's interest since it calculates what is the most suitable action to take. When there are very few vehicles, the interests might have to travel farther to get an acceptable response. That is why SCAMP does more matchings than Geocast with low vehicle density. When the vehicle density increases, Geocast does more matching because of more generated forwarding and replying packets.

5.5.5 Centralized or opportunistic?

5.5.5.1 Parking system occupation

Parking occupancy rate affects the economic benefits of the city. When the parking demands are less than the parking places, the occupancy rate is at most the quotient of the amount of drivers searching for a place to park divided by the total available parking places. If the amount of drivers is more than the amount of parking places, the smart parking system becomes an important key factor to provide the available parking information to drivers. In Fig. 6.17, the centralized method provides a better

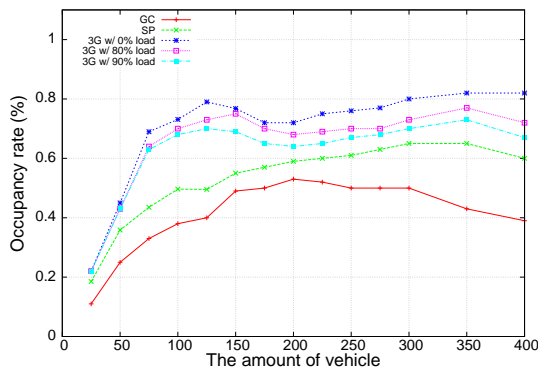


Figure 5.27: Occupancy rate of 100 parking spaces in an area of $3 \times 3 \text{ km}^2$

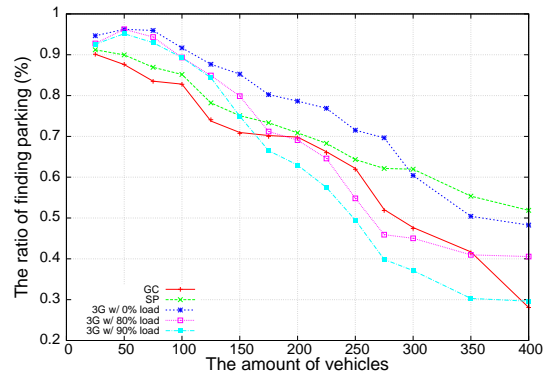


Figure 5.28: Successful ratio of finding parking in an area of $3 \times 3 \text{ km}^2$

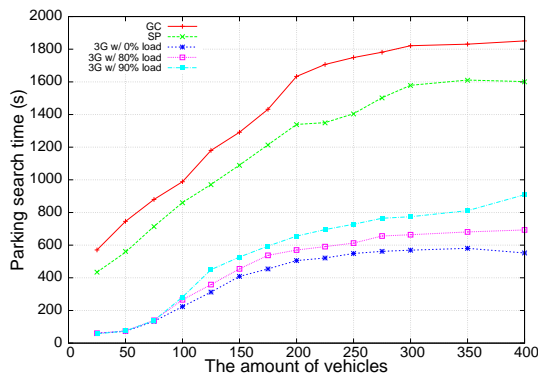


Figure 5.29: Required time to find a parking place in an area of $3 \times 3 \text{ km}^2$

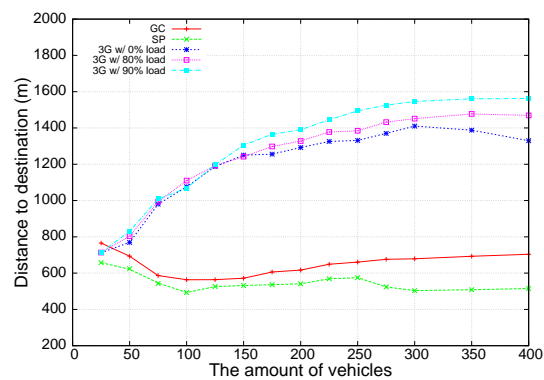


Figure 5.30: Distance from parking to destination in an area of $3 \times 3 \text{ km}^2$

connectivity so that most drivers are informed of the available parking places. When the load of BTS (base transceiver station) is increasing, drivers' demands cannot always be processed right now, the occupancy rate then drops. Geocast and SCAMP both have a lower occupancy rate, however, SCAMP can benefit from its fewer packet retransmissions to diffuse the information to farther drivers. When the amount of vehicles increases, it leads to a disaster of packet collisions and drop the network throughput, hence drivers cannot get the information and there is a fall in occupancy rate.

5.5.5.2 Drivers' satisfaction

The chance to find a parking place is related to the competition level (the amount of drivers searching for parking versus the amount of available parking). Whatever the communication technology is used, the successful rate is inversely proportional to the amount of vehicles in Fig. 6.16. The centralized method shows clearly that the chance decreases according to the load and the demands. The opportunistic methods relies on certain amount of participants to disseminate between information inquirers and data owners. Yet, Geocast only considers the network level and generates too many packets as the amount of vehicles increases. SCAMP, which eliminates the necessary packets

according to the content matching, can take advantage of vehicular density. Cellular network provides prompt response thus the parking search time is shorter. In vehicular network, the response can arrive after several minutes. Fig. 6.14 shows that the parking search time correlates with the network latency and then increases when the amount of drivers chasing the same parking area grows. Although cellular network can have the global information and provides all the possible parking places to drivers, the parking distance is often far. From Fig. 6.15 shows that vehicular network keeps local information for drivers nearby to get a closer spot by chance. If a place is suddenly released, the direct communication from a neighbor RSI or vehicle is more timely than cellular network.

5.6 Summary

Content-based Publish-Subscribe system provides more matching expressions to give a finer notification. Many machine learning algorithms have been proposed to build a more intelligent semantic system according to users' interests. In this chapter, we proposed an extended version of Publish-Subscribe system which adapts users' subscriptions, calculates matching quality and evaluates drivers' mobility in order to spread information in a better manner. We then evaluated our model in a dynamically moving vehicular network with different routing parameters. We also compared our model with mobile network to see if opportunistic network can be considered as an alternative. The results show that even opportunistic network cannot be as efficient as mobile network, it can still provide a quite good parking service with a shorter walking distance. While the mobile network has too much load and the parking demand is very high, our model SCAMP can even outperform the pure Publish-Subscribe service in mobile network. Some subsequent questions are coming, for example, if drivers are willing to participate vehicular information network, if the service can be supported in heterogeneous network, and how the parking game happens among drivers. We will discuss them in the next chapter.

Information Dissemination for Smart Parking Service

6.1 Introduction

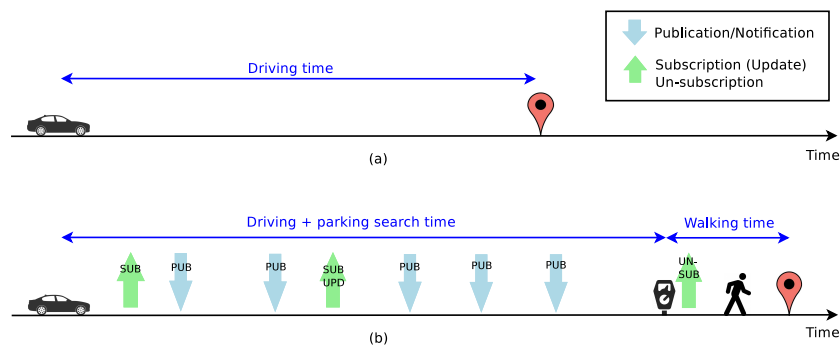


Figure 6.1: The timeline of a driver while travelling to a destination: (a) without parking worry (b) including parking search time with the aid of Publish-Subscribe service.

Cities are in readiness for urban service thanks to the popularity of smartphones and the rise of connected vehicles. Drivers can access to the service while being opportunistically connected to the infrastructure or any data storage. In Fig. 2.3, we have induced seven different ways to deliver parking information to drivers. Among them, vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) give a flexible extension to current city infrastructure, from the viewpoint of either distributedly or centrally information-assisted, and even hybrid of them.

Although some results show the advantages of sensor-to-vehicle communications [161], sensor's battery lifetime is still awkward to handle. Even there are many propositions of using parked cars to improve service availability [254], cars still suffer from limited battery capacity and cannot provide some extra services while being parked. Many cities consider smart parking as an inception of smart city [7], especially the deployment of smart parking meters. Parking meter cannot only collect information from roadside sensors, but also be considered as a service agent, providing parking information to passing drivers through wireless communications. That is, the roadside equipment can increase service availability and give a promising future to vehicular network [255].

When it comes to drivers' feelings, we first look at the timeline of a driver's trip, shown in Fig. 6.1(a). A driver chooses a destination and then heads to it. In reality, the

driver has to search a parking place blindly and walks from the parking place to the destination after his/her arrival, shown in Fig. 6.1(b). Thus, the travel time is counted by summing up the durations of driving, parking search and walking. The driving time is related to the travel distance and the real-time traffic. The parking search time and walking distance are relevant to traffic congestion, occupancy and turnover rates. An information-assisted smart parking service can inform drivers of available parking places so as to shorten the parking search time. If driver can get one parking place in the vicinity of the destination through the smart parking service rapidly, namely the walking distance is short and the parking search time is short, s/he will consider this service is good.

In Chapter 5, we proposed an extended Publish-Subscribe service to notify drivers of parking places which match their custom interests. Publish-Subscribe messaging diagram can avoid the repeated parking search, because drivers keep receiving update information at the wheel. We then showed that drivers' satisfaction can be affected by different communication methods according to their mobility.

In this chapter, we extend the results in Chapter 5 to discuss the information dissemination ways for smart parking service. We first define a parking game. From drivers and city's utility functions, we remark the important parameters. We also explain our simulation environment considering the dynamic urban environment. Then, to verify the common freerider problem in a crowdsourced dissemination platform, we evaluate different participation rates of pure Publish-Subscribe and our model SCAMP. By undertaking the parking game, we then evaluate our model in an heterogeneous network to see if it works efficiency.

As such, the information dissemination for smart parking service is strongly related to drivers' mobility, drivers' behaviors and communication methods. If an urban service is designed with taking these factors into account, it might be useless and even paralyze the network. This chapter has the following three contributions: First, we formulate an on-street parking game and provide their utility functions, allowing to explain the results we get and being used as drivers' parking decision later. Second, we apply different participation rates in the partial crowdsourcing parking service system, supporting by vehicles and RSI, in order to see how users' satisfaction is influenced. Third, we simulate our model in an heterogeneous network, mixing with mobile and vehicular networks, to show our model can still be supported and even compensate for drawbacks of the two different networks.

6.2 Related works

Parking game

The personalized service consideration is always an issue while providing services to users, especially for highly interactive traffic-related applications. If several drivers ask for parking places in the same area simultaneously and they all receive the same information, it implies that all the drivers will be guided to the same destination along

the same path. For some hot spots in city center, there will be always traffic jams and parking search conflicts which make drivers to give up the useless smart parking services. Karaliopoulos [181] proposed a game-theoretic model to see whether drivers choose to compete these limited on-street parking places. Driver's decision leads to three results: Drivers who go to the private parking directly, those who decide to compete the on-street parking and find one, and those who finally fail to find on-street parking and change to the private parking. Kokolaki [182] studied the same problem with the consideration of a parking information-assisted system, thus driver's decision changes according to the amount of competitive vehicles and the current available parking spaces. Hence, the competitor amount varies over time through the real-time information from smart parking service. Ayala *et al.* [174–177] focused on the parking competition. Each driver shall be assigned a parking place s/he prefers, or the parking assignment will not be stable, to wit, stable marriage problem. Authors modeled the parking decision by a gravity-based parking algorithm and a game theory model. That is each driver will calculate the gravity value of each parking place with respect to him/herself and his/her neighbors. If his/her gravity value is higher than others, s/he will take this parking place.

Crowdsourcing

Since the urban service deployment is strongly related to human activities, crowdsourcing platforms supported by service users themselves are more and more popular. Even Pandey *et al.* [246] proposed to use city buses to spread information, the bus trace is regular and also the parking need is high on vehicles' cruising areas which might quite different from those of buses. However, users may reject to forward or reply to messages because of battery concerns or other egoistic reasons. The incentive is always chiefly concerned with all crowdsourcing platforms [90; 95; 256]. If no vehicle forwards any message in an infrastructure-assisted crowdsourcing service system, it will downgrade to a single-hop broadcast-like protocol [257].

Information dissemination

Leontiadis *et al.* [258] introduced a topic-based Publish-Subscribe communication paradigm to opportunistically disseminate information in vehicular networks. The subscriptions were generated from vehicle's navigation system to know driver's destination and current location. Authors used the realistic traffic traces in Zurich¹ to simulate vehicle mobility. The results only show the performance from network's viewpoints, such as message delivery ratio, overhead and the number of replicas. Rajabioun *et al.* [6] revealed the problem of disseminating information in the on-street parking guiding system. That is the real-time parking availability data is useful only when the driver is very close to the parking location.

¹www.lst.inf.ethz.ch/research/ad-hoc/car-traces/

6.3 Parking game

Parking competition is often considered as a parking game. The payoff is usually counted from a comprehensive consideration of parking search time, parking fee and walking distance. Most time, the off-street parking has enough capacity to receive those cruising drivers. However, drivers might flinch from higher parking fees and prefer to turn around their destinations to wait for a god-given gift, namely a cheap or free street parking place.

6.3.1 Parking search time

Drivers usually have three choices to park their cars: on-street, off-street parking or illegal areas. From [5], we see that if the fraction of being caught is high, the illegal parkers will be fewer as well. With the aid of parking sensors, it will be quite easy to be reached. Drivers, who get on-street parking via blind search, usually spend an exponential duration to find a parking place [4]. Thus, the on-street parking search time can be expressed as below:

$$t = \alpha e^{-\beta R_{cong}} \quad (6.1)$$

α and β are structural parameters and can be obtained by collected data. For example, from all-survey data in Lyon, $\alpha = 0.217$ and $\beta = -7.364$. R_{cong} , congestion ratio, is calculated by the amount of parked vehicles in legal parking areas (V_{occ}) and in illegal areas (V_I) divided by the amount of parking places (K). From Section 5.5.5 and [160], it is obvious that information-assisted smart parking system can help to reduce the parking search time during high traffic congestion ratio.

Drivers choosing off-street parking are often those who cannot find an on-street parking place and finally look for a private car park. Thus, the parking search time for off-street parking is usually longer and validated by Axhausen's formulation, in Eq. 6.2.

$$t = \frac{\alpha}{1 - \frac{V_{occ}}{K}} \quad (6.2)$$

6.3.2 Parking search cost

In such a context, when X vehicles pursuit Y on-street parking and $X > Y$, we can split X into two groups: Y_0 and $X - Y_0$. If $Y_0 > Y$, at least $(Y_0 - Y)$ drivers will suffer from the endless parking search (Eq. 6.1). Thanks to the smart parking service, Y_0 is usually smaller than Y [182]. From the results in Chapter 5, we are able to formulate the on-street parking game. In order to define the parking game, we set drivers as players, parking choices as the set of actions ($S_i = \{choose, not_choose\}$) and a set of preferences which affect the payoffs. Then the payoffs are shown in Table 6.1. The payoffs of driver i are in blue, and in red for the other $Y_0 - 1$ drivers.

Action set i		Action set $Y_0 - 1$	
		All all the other $Y_0 - 1$ drivers	
		choose $(\sigma_{i,j})$	not choose $(1 - \sigma_{i,j})$
Driver i	choose $(\rho_{i,j})$	$(C_j P_{i,j} + C_{gas}^* P_{i,j}^*, C_j^* P_{i,j}^* + C_{gas} P_{i,j})$	$(C_j, C_{gas}(Y_0 - 1))$
	not choose $(1 - \rho_{i,j})$	(C_{gas}, C_j^*)	$(C_{gas}, C_{gas}(Y_0 - 1))$

Table 6.1: Incomplete Information parking game: driver i versus parking place j

$\rho_{i,j}$ is the probability that the driver i chooses the parking place j . $\rho_{i,j}$ is generally affected by driver's mental preferences, such as parking fee, walking distance and the cumulative parking search time [259]. $\sigma_{i,j}$ is the probability that at least one driver among the $(Y_0 - 1)$ chooses the parking place j , and can be expressed as below:

$$\sigma_{i,j} = 1 - \frac{1}{1 - \rho_{i,j}} \cdot \prod_{k=1}^{Y_0} (1 - \rho_{k,j}) \quad (6.3)$$

C_j is the fee of one parking place j . C_{gas} is the extra fuel cost for one vehicle to look for next parking place. If a driver retries several parking searches, the cumulative cost can be stunning. Then $\rho_{i,j}$ will be influenced as well [259]. C_{gas}^* is the cost for at most $(Y_0 - 1)$ vehicles which fail to get the parking place j . C_j^* is the cost if one vehicle among $(Y_0 - 1)$ gets the parking place j . C_{gas}^* and C_j^* can be calculated by the following equations.

$$C_{gas}^* = C_{gas} \cdot (Y_0 - 1) 2^{Y_0 - 2} \quad (6.4)$$

$$C_j^* = C_j \cdot (2^{Y_0 - 1} - 1) + C_{gas} \cdot ((Y_0 - 3) 2^{Y_0 - 2} + 1) \quad (6.5)$$

$P_{i,j}$ is the probability that driver i gets the parking place j successfully. The chance to get a parking place is often related to the distance between driver's current position and the parking place [6]. Let set $d_{i,j}$ as the distance from driver i to parking place j . Then $P_{i,j}$ can be expressed in Eq. 6.6. $P_{i,j}^*$ is the probability that driver i fails to get the parking place and $P_{i,j}^*$ is equal to $1 - P_{i,j}$.

$$P_{i,j} = \frac{d_{i,j}^{-1}}{\sum_{k=1}^{Y_0} d_{k,j}^{-1}} \quad (6.6)$$

The utility function from the viewpoint of driver can be calculated by referring to Table 6.1. The utility will be to minimize the total travel cost, shown as below:

$$\begin{aligned} M_i(S_i, S_i') &= (1 - \rho_{i,j}) C_{gas} + \rho_{i,j} \sigma_{i,j} (C_j P_{i,j} + C_{gas}^* P_{i,j}^*) + \rho_{i,j} (1 - \sigma_{i,j}) C_j \\ &= C_j (\rho_{i,j} - \rho_{i,j} \sigma_{i,j} + \rho_{i,j} \sigma_{i,j} P_{i,j}) \\ &\quad + C_{gas} (1 - \rho_{i,j} + \rho_{i,j} \sigma_{i,j} (1 - P_{i,j})) (Y_0 - 1) 2^{Y_0 - 2} \end{aligned} \quad (6.7)$$

Additionally, the utility function from the viewpoint of the municipality is different. The city only cares if the parking place is used, not who is parking on it. Thus, the utility

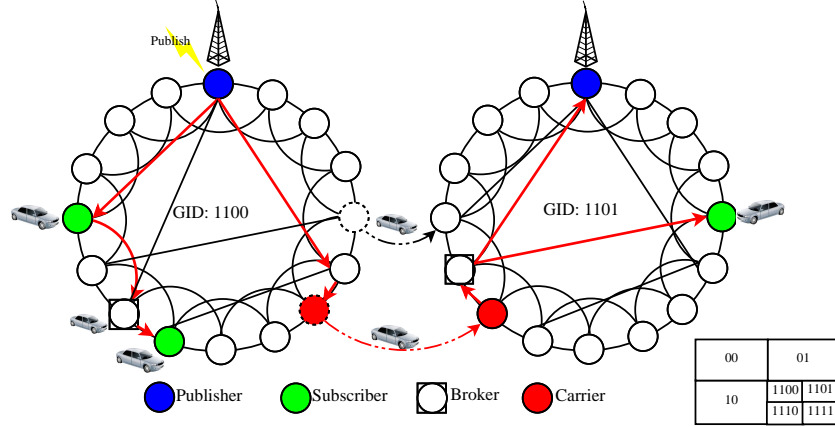


Figure 6.2: Illustration of Publish-Subscribe service supporting by moving vehicles and roadside infrastructure.

will be to maximize the revenue and minimize the CO₂ emission.

$$\begin{aligned}
 M_{mun}(S_i, S'_i) &= (\rho_{i,j} + \sigma_{i,j} - \rho_{i,j}\sigma_{i,j})C_j^{*'} - (1 - \rho_{i,j})(1 - \sigma_{i,j})Y_0C_{gas} \\
 &= C_j(\rho_{i,j} + \sigma_{i,j} - \rho_{i,j}\sigma_{i,j})(2^{Y_0-1} - 1) \\
 &\quad - C_{gas} [(\rho_{i,j} + \sigma_{i,j} - \rho_{i,j}\sigma_{i,j})((Y_0 - 3)2^{Y_0-2} + 1 - Y_0) + Y_0]
 \end{aligned} \tag{6.8}$$

In Eq. 6.7, the utility of a parking place for a driver is principally determined by $P_{i,j}$ and Y_0 . When there are fewer competitors (Y_0 is small) and driver is close to this parking place ($P_{i,j}$ is high), this parking place is more useful. However, from the municipality's viewpoint in Eq. 6.8, if Y_0 is high, namely more drivers know the parking place is available, the city has more chance to issue a parking ticket and increase parking revenue.

6.4 A smart parking semi self-service system

6.4.1 System overview

In V2V and V2I networks, the packet transmission is done by vehicles and RSI. RSI is often installed at crossroads in order to communicate information to a large number of cars [260]. RSI usually plays the role of gateway to collect information as a mini distributed data center. In key-based routing, we assume there is at least one The information. If a driver sends a parking query and a nearby RSI has the appropriate information, the RSI will reply directly to the driver. Otherwise, other vehicles or RSIs hearing this query will forward this query to the destination of this query. Similarly, if a sensor changes its sensing state and informs its attached RSI, the RSI will send out the messages to the network. Each device then compare the publication with its own subscription table to see if any of its neighbors is interested in this information. Thanks to the mobility of vehicles, they can try to carry the messages far in order to let more drivers be informed of parking availability information. Jiang [261] studied the topological pattern of urban street network and demonstrate its small world structure.

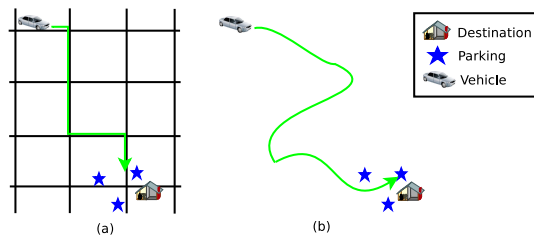


Figure 6.3: Mobility models: (a) Synthetic with geographic-restricted pathloss (b) Real vehicular trace with free space path loss.

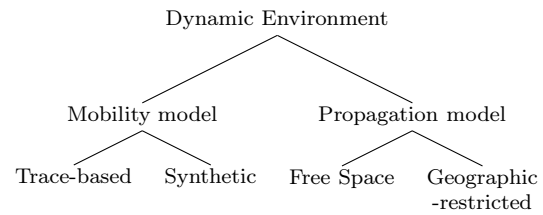


Figure 6.4: Dynamic environment simulation diagram

Cunha [262] shows that the vehicular mobility presents a small-world behavior by analyzing the vehicle traces from San Francisco and Zurich. We then assume that mobile vehicles and fixed RSIs form several network clusters and each cluster can be regarded as a small world. Fig. 6.2 illustrates how the Publish-Subscribe can be supported by moving vehicles and RSI.

6.4.2 A more realistic urban environment?

While simulating dynamic urban environment, mobility and propagation models are two important factors (Fig. 6.4). Dynamic environment can be simulated by the combination of mobility and radio propagation models. Mobility model is used to describe drivers' mobility. Trace-based vehicular mobility describes the inter-contact times and duration between vehicles. It also provides more realistic probabilities of sending out messages. Synthetic models allow to reproduce drivers' mobility and show the impact from application on waypoints.

After looking at the mobility, the radio propagation is also very important. In reality, wireless communications are very sensitive to the urban terrain, such as buildings, urban objects or vehicles. Thus, a realistic geographic-restricted pathloss model is required to describe the channel properties. Ideally, a combination of a real vehicle trace and a geographic-based pathloss model will be perfect to evaluate vehicular services. However, pathloss calculation shall be modelled from collected data of link quality. It is quite difficult to combine them. Thus, most traced-based mobility model often adopts a free space pathloss model which only considers the distance between senders and receivers, in Fig. 6.3(b). Geographic-restricted pathloss is then possible to implement with synthetic mobility models since the mobility environment is pre-defined according to the context, in Fig. 6.3(a).

Although trace-based mobility data evokes great interest, we cannot add the impact of messages on it. That is to say, vehicles can only move by following the time-varying waypoints. The smart parking service is to help drivers find a satisfied parking place. Drivers' speed and heading direction shall be influenced by receipt messages. Some works tried to find out some mobility characteristics, for example, [263] sorted out the average stay time of vehicle in each grid of 1x1km and verified the model with vehicle density and [264] induced all the possible speeds, directions, pause time and durations from user

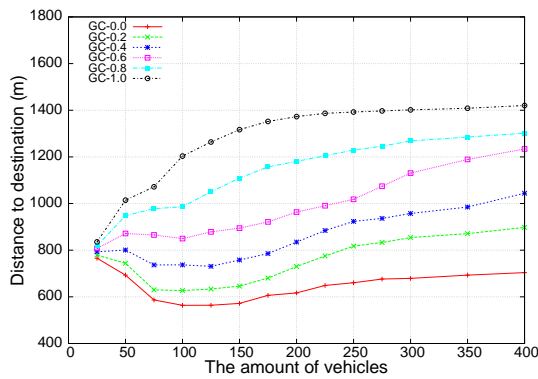


Figure 6.5: Distance from parking to destination in an area of $3 \times 3 \text{ km}^2$ via Geocast with different participation rates

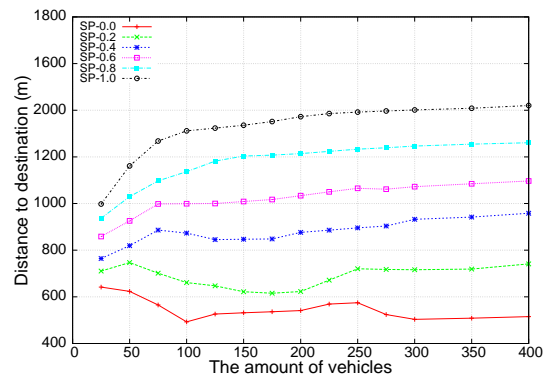


Figure 6.6: Distance from parking to destination in an area of $3 \times 3 \text{ km}^2$ via SCAMP with different participation rates

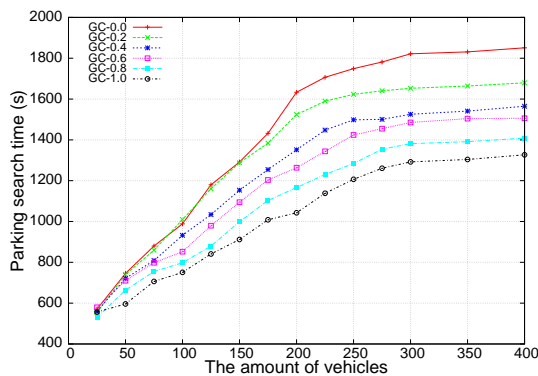


Figure 6.7: Required time to find a parking place in an area of $3 \times 3 \text{ km}^2$ via Geocast with different participation rates

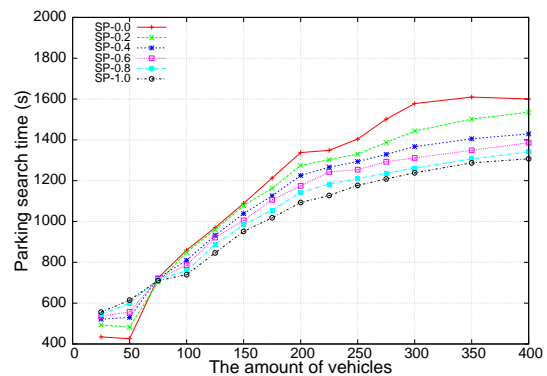


Figure 6.8: Required time to find a parking place in an area of $3 \times 3 \text{ km}^2$ via SCAMP with different participation rates

traces. We still cannot really model the impact from applications and make sure that the mobility is yet realistic. In short, the mobility model we used in Chapters 5 and 6 combines the parking behavior in Figs. 5.6 and 6.3(a).

6.4.3 Freerider evaluation

Since opportunistic network relies on the cooperation of users, the participation rate ρ is very important for the system performance. We assume all the nodes are equipped with vehicular communications and can receive messages in the network. RSIs always do the matching and give a response if needed. Vehicles or drivers can choose to execute matching or forward messages according to their wishes. We then give several different participation rates and see how it impacts on drivers' satisfaction. The simulation parameters are shown in Table 5.2 and performed with the WSNET simulator [228].

Fig. 6.5 shows the parking distance to driver's destination via Geocast. If all the drivers cooperate together ($\rho = 1$), the parking information is disseminated farther and drivers

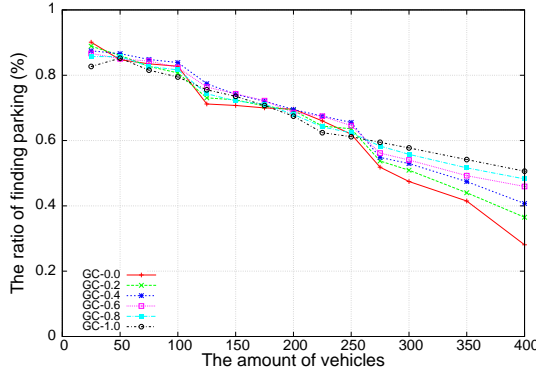


Figure 6.9: Successful ratio of finding parking in an area of $3 \times 3 \text{ km}^2$ via Geocast with different participation rates

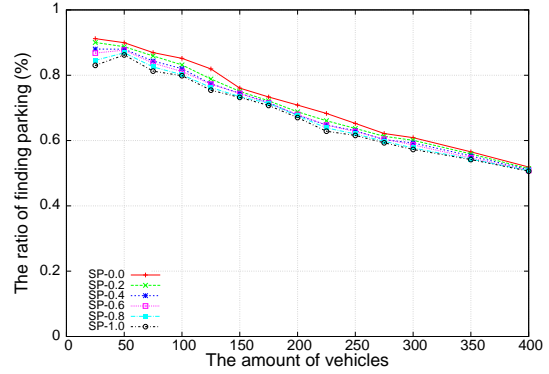


Figure 6.10: Successful ratio of finding parking in an area of $3 \times 3 \text{ km}^2$ via SCAMP with different participation rates

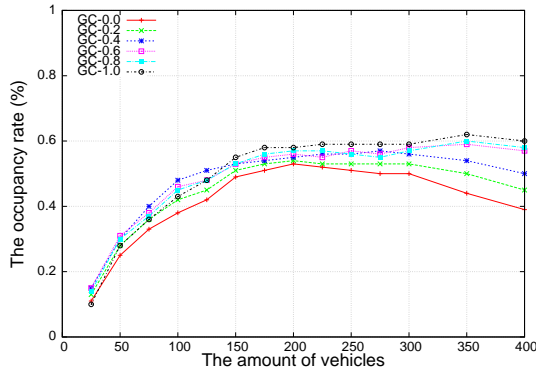


Figure 6.11: Occupancy rate of 100 parking places in an area of $3 \times 3 \text{ km}^2$ via Geocast with different participation rates

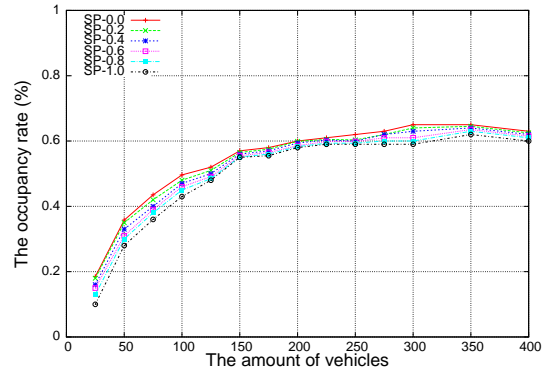


Figure 6.12: Occupancy rate of 100 parking places in an area of $3 \times 3 \text{ km}^2$ via SCAMP with different participation rates

have chance to find a better (closer) parking place. If there are too few vehicles, the information dissemination rate is decreased and the average parking distance is also longer. When the vehicle density raises, the parking search becomes more competitive so that the parking distance increases again. Since SCAMP applies the action table according to the information quality, some information might not be sent and the parking distance is farther in Fig. 6.6. With the increasing of vehicle density, vehicles can find a better parking until the parking is saturated. Both Fig. 6.5 and 6.6 show that if ρ reduces ($\rho \rightarrow 0$), the information dissemination rate is lower and the average parking distance is farther. When $\rho = 0$, both Geocast and SCAMP downgrade similarly to one-hop broadcast [257].

On the contrary, the parking search time is shorter if vehicles cooperate less. That is because there are less parking competitions when the information does not travel far. In Fig. 6.7, we see that the lower participation rate in Geocast also results in fewer packet collisions. As ρ decreases, the parking search is significantly faster. However, SCAMP generally has similar characteristics as Geocast in Fig. 6.8. But when the ratio

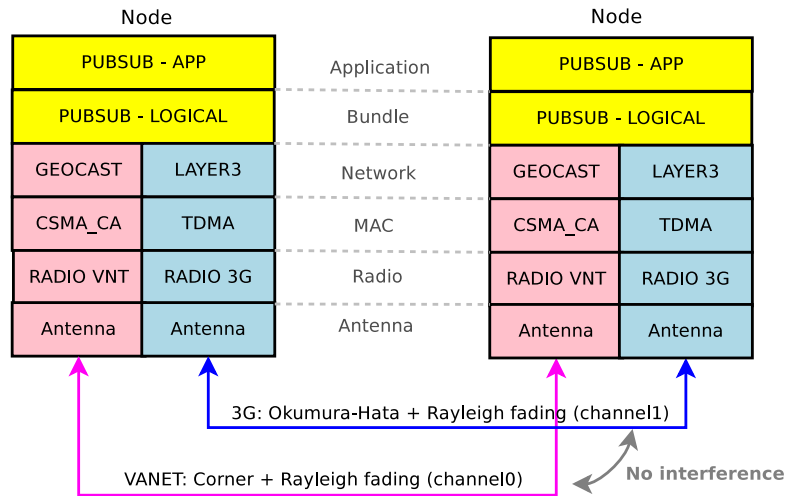


Figure 6.13: An overview of heterogeneous network

of vehicles to parking places is smaller than 1 in SCAMP, $\rho = 1$ can still outperforms $\rho = 0$. Even it generates a bit less publication and vehicles need more time to find a parking place while vehicle density is very low.

In terms of the successful ratio of finding a parking, we see that SCAMP outperforms Geocast in Fig. 6.9 and 6.10. Generally speaking, Geocast has the better performance when there are fewer participants forwarding messages as the vehicle density increases. When there are 50-250 vehicles, $\rho = 0.4$ and 0.6 have a better successful rate thanks to fewer but not too few retransmissions. When there are a lot of vehicles, 0% of participation is the best case to disseminate parking information. SCAMP has a quite consistent performance whatever the amount of vehicles varies.

The drivers' satisfaction is of course important. Nevertheless, the municipality cares even more if the parking places are used profitably by drivers. In Figs. 6.11 and 6.12, we first see the occupancy rate is higher as the amount of vehicles increases, namely there are more parking demands. After the parking demands are more than certain amount, the occupancy rate does not increase anymore and remain at a value. Geocast, which does not consider the information content and forwards too many messages, has severe packet collisions which drop the network efficiency. When no vehicle joins message forwarding, the RSI will provide information directly to passing vehicles via one-hop. Instead, SCAMP can reduce the packet collisions and improve the service availability slightly when all drivers participate the information spreading, shown in Fig. 6.12.

6.5 Heterogeneous network

With the popularity of smartphone and connected cars, users often hold a device which supports several different mediums. Now it is very common that if users cannot get enough medium resource from mobile network, they switch right now to WiFi access

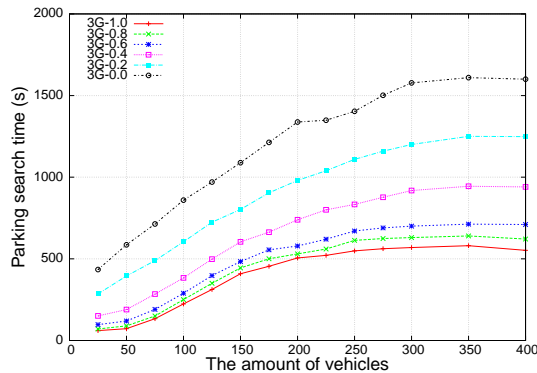


Figure 6.14: Required time to find a parking place via heterogeneous networks in an area of $3 \times 3 \text{ km}^2$

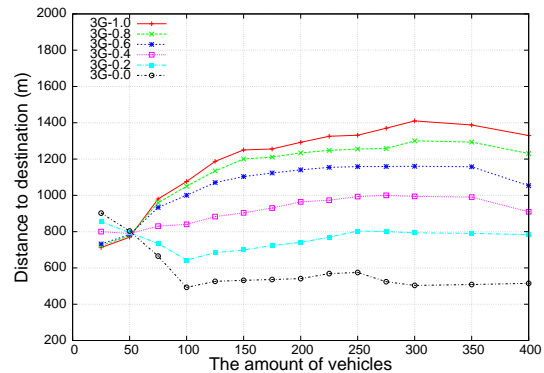


Figure 6.15: Distance from parking to destination via heterogeneous networks in an area of $3 \times 3 \text{ km}^2$

points or even to point-to-point bluetooth communication. Vehicular network adopts the IEEE 802.11p² standard and basically uses carrier sense technology to allocate bandwidth dynamically. IEEE 802.11p benefits from its compatibility with WiFi and can be seen as an offloading alternative.

6.5.1 Protocol stack

In order to make the offloading test, we implemented a multi-interface bundle in the WSN_{ET} simulator [228]. the Publish-Subscribe messaging paradigm is a cross-layer protocol which involves the application and logical layers. The logical layer is equivalent to the bundle protocol described in RFC 5050³. In Fig. 6.13, the yellow bricks is for the Publish-Subscribe service, where we implemented our SCAMP model. The pink bricks represent the protocol stack for vehicular networks. The blue bricks represent the protocol stack for mobile networks. In vehicular network, we adopt the Corner propagation considering our mobility model. In mobile network, Okumura-Hata is used. The two environments both apply single-channel and have no mutual interference. A smart device shall be able to detect the data rates and prices of different interfaces in order to evacuate queued packets more rapidly. We are then interested in knowing what is the trade-off of mobile offloading with respect to the quality of smart parking service.

6.5.2 Why mobile offloading

From Figs. 6.17 to 6.15, we see three facts: First, mobile network, benefiting from its large communication range, can provide drivers promptly with parking information. Second, drivers might give up searching for a parking place close to its destination but far from its current location because of the central information from mobile network. Thus, drivers connecting to vehicular networks can have chance to get a closer parking place since the information dissemination is pretty local. Third, mobile network is

²www.standards.its.dot.gov/Factsheets/Factsheet/80

³www.rfc-base.org/rfc-5050.html

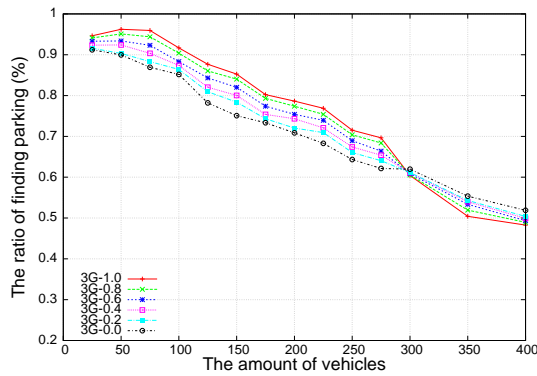


Figure 6.16: Successful ratio of finding parking via heterogeneous networks in an area of $3 \times 3 \text{ km}^2$

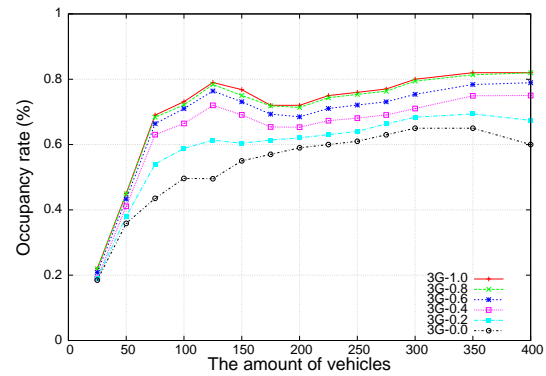


Figure 6.17: Occupancy rate of 100 parking spaces via heterogeneous networks in an area of $3 \times 3 \text{ km}^2$

usually a favorable communication way for cities according to Eq. 6.8. It increases the on-street parking occupancy rate instead of thinking about the utility of drivers in Eq. 6.7.

In this section, we will split the traffic of each device into two groups. One is injected into vehicular networks, the other is for mobile network. That means that a driver might send his/her subscription through mobile network, and get a notification through vehicular network. It might help find an equilibrium point between city and driver's utility.

6.5.3 Traffic trade-off evaluation

From Fig. 5.26, we know that the publication (notification) does not have to forward many times in order to reach subscribers. While reducing the amount of transmissions through mobile network from 100% to 60%, the parking search time and walking distance change insignificantly, shown in Figs. 6.15 and 6.14. Drivers might receive the information of closer parking places through vehicular network, so that the parking search time increases, i.e., drivers have to pilot longer to arrive his parking place but the walking distance is reduced. Besides, vehicular network is semi-spontaneous and relies on drivers themselves to create a dynamic information platform and share mutually. When the vehicle density is too low, the information cannot be disseminated widely. That is why the walking distance is farther when there are less than 50 vehicles in Fig. 6.15.

Since mobile network does not perform repeated transmissions to enlarge packet receipt rate, only few percentage of network traffic from mobile network with the existing vehicular network can always improve the performance significantly, shown in Fig. 6.16.

The parking system occupancy is revealed in Fig. 6.17. Even 80% of packets are send by vehicular network, the occupancy rate is always improved a lot, especially when the vehicle density is low, central message transmissions can largely increase the efficiency

of information dissemination.

6.6 Summary

To search an on-street parking place in urban areas is always a nightmare for drivers. Thanks to the information communications technology, drivers themselves can form a parking information platform and cooperate with the infrastructural databases. This chapter has presented a parking game model considering drivers' preferences, their geo-locations and the amount of competitors. We then derived the utility of a parking place from the viewpoints of drivers and city. Next, with the partial crowdsourcing vehicular information platform, we changed the participation rates of drivers to see how it impacts to the service quality. Then by combining the results from the previous chapter and our game model, we evaluated our model in an heterogeneous network, including mobile and vehicular network, to give an equilibrium point from their completely different characteristics.

Many current studies propose different Publish-Subscribe solutions. They either only work on the application layer, or simulate the performance without considering the problem of packet collisions in wireless networks. Our work mainly includes comprehensively from application to radio layers in an expedient dynamic environment. The results show that our model is really effective to compensate the shortage of vehicle-to-infrastructure communications through vehicle-to-vehicle communications, and it also works well in an heterogeneous environment.

Our work can be validated later with a reactive vehicle trace in order to get a more reliable, realistic and feasible solution. The game theory model can also be implemented to take parking choices by referring the survey data from other domains.

Part IV

Now and the Future of Smart Parking

Conclusion and open perspectives

7.1 Conclusion

Unquestionably, parking is really a pain for all drivers in the world. With the parking information, collected either from the parking sensors of cities or from crowdsensing apps, smart parking service can provide a platform with the real-time parking status for drivers. Thanks to it, drivers can shorten their travelling time and the city can increase the revenue from parking fees and tickets. Most smart parking implementations focus on the sensing technology and the development of mobile apps. For this reason, city's deployment builds a bridge between them. The large-scale deployment is a good opportunity to test the sensing accuracy and sensor's connectivity [1; 91]. The sensed information can be stored in servers and provide information to the current apps.

Before coping with the annoying parking problem, we summarize a taxonomy of smart parking solutions in Chapter 2. We divide them into three different groups: information collection, service deployment and service dissemination. All the works are visualized in the detailed tables to show the different research focuses. Information collection involves the sensing technology, wireless sensor network and crowdsensing. Service deployment includes software system, large-scale deployment and availability prediction. Service dissemination is related to information dissemination, parking competition and drivers' behaviors.

However, the deployment and the maintenance of parking sensor networks are not easy. The message timeliness, the autonomy and self-healing of sensor network all rely on the wireless communication. Although there are many researchs on wireless sensor networks, very few of them aim at deploying on parking places. We explore the sensor deployment from network perspective, in Chapter 3. From the limited real implementation, we extract the traffic model and then reproduce it in our simulation so as to evaluate its impact to the network performance. Then, we expand this network infrastructure to assess the required hardware equipments. We show the network latency is positively correlated with the deployment cost, in Chapter 4.

Merely the parking information cannot ease drivers' headache. From the current survey in Chapter 2, very few cities can really provide the real-time parking availability information to drivers. Either the information is often outdated, or the mobile network is too slow to inform drivers of new parking status. Since most cruising drivers are tourists who are unfamiliar with the city, they might not be able to obtain information through the mobile network. Even if drivers can access the information, they might choose to

chase an optimal but a little far parking place to result in a parking competition, in Chapter 6. As the opportunity for the connected car market is huge, we simulate our model in vehicular network. However, there are many existing challenges and vehicular network is more sensitive to urban environment. We then construct our simulation with an urban propagation model and a specific mobility, including parking behavior.

Additionally, the current smartphone apps are not proactive. That is not convenient for drivers cruising on the street. Therefore, in Chapter 5, we propose an extended version of content-based Publish-Subscribe service, allowing to display the information, which matches drivers' interests, automatically on drivers' smartphones. In order to increase the packet delivery rate and to reduce the network load, we implement an analyzer of information quality. For those who cannot provide a good quality of information after matching, they will not execute message replying or even forwarding. If a device does not head the same direction with a receipt message, it will not be the message carrier either. After a series of evaluation, we find the suitable routing parameters and it outperforms pure Publish-Subscribe system, with respect to grid size, ratio of parking demand to supply, transmissions, matching times, and user participation rate, user's satisfaction and system occupancy rate, in Chapters 5 and 6.

Our work is based on the premise that large-scale parking sensors are deployed in the city. We look at the whole picture of urban service from viewpoint of the municipality and drivers. As such, we shed light on two main topics: the information collection on sensor deployment and an extended version of content-based Publish-Subscribe messaging paradigm.

For the first topic, we see four facts. First, magnetometer and smartphone are the two main parking sensors for municipal deployment and user-generated content, respectively. Second, a schedule-based MAC will be the trend thanks to its easy management and low energy consumption. However, the signaling and scheduling arrangement are more complex. Third, event-driven and periodic hybrid application models are more suitable to adapt different urban applications. Fourth, large-scale sensor deployment will be more and more common. Intersections become the important places to install urban infrastructure.

For the second topic, we also get four facts. First, roadside infrastructure, which can be WiFi access points or parking meters, can efficiently increase service's availability through vehicle-to-vehicle or vehicle-to-infrastructure communications. Second, drivers, chasing the limited parking place, form a parking game and evaluate their parking choices by the utility function. Third, Publish-Subscribe messaging paradigm is the most suitable protocol to match drivers' interests and available parking information. Fourth, the communication method can have a great impact on Publish-Subscribe. Our work gives a guideline from network-related perspectives for cities before launching smart parking or any similar real-time urban service projects.

7.2 Open perspectives

Even there are many great crowdsensing concepts to gather parking information, big cities still prefer to deploy their own smart parking solutions so as to really manage their own belongings and data [5; 7; 265]. Moreover, these parking sensors and their infrastructure, integrated with other types of sensors, can form a huge sensing platform, named smart city. That is to say, smart parking has been opening the prelude of city's reform. More and more heterogeneous information circulates on network and the maintenance is costly, so that the need of message filtering, to remove the redundancy of information, is more and more important. Such kind of network is called Named Data Network (NDN) [266; 267], which is a multi-campus research project¹. In which, service users merely have to know what kind of data they are interested in instead of knowing the host address. However, NDN requires a lot of realistic data to assess its feasibility and performance. We then open up some research direction by undertaking our work.

First, the heterogeneity in sensor networks is more and more obvious. The traffic model changes accordingly. With one unique application in sensor network, the quality is still predictable. While considering several heterogeneous applications, the quality is somehow complicated to promise, for example, some related problems, i.e., the scheduling and coverage. Gaillard *et al.* [268] presents the challenges while sharing the WSN resource among various clients, and distinguishes the various formal algorithms that are necessary to operate a WSN according to service level agreement. If the system is not well adapted to different heterogeneous sensor flows, it might drop the performance or even paralyze the network functionality. Thus, all what we have simulated in smart parking, in Chapter 3, shall be evaluated in heterogeneous sensor network to see the pros and cons.

Second, the capacity of gateways might be limited by the connections of a lot of different heterogeneous sensors and routers. Even some sensors can use long-range consumption to send out their information, the amount of transmissions is still limited. It will be more efficient to manage and optimize those heterogeneous sensors, if we can have their traffic models and apply them according their geo-locations in the map. This way, we will be able to undertake the work in Chapter 4 to consider their clustering relationship and if each gateway achieves its maximum capacity.

Third, the deployment of urban infrastructure in Chapter 4 only considers parking sensors. In Chapters 5 and 6, we deploy roadside infrastructure randomly in one intersection of each grid. Urban infrastructure is the principal portal for drivers to access city information. Mehar *et al.* [260] proposes an optimized roadside units placement for delay-sensitive application in vehicular networks. Smart parking is a real-time urban service and may be able to adapt to this optimization application.

Fourth, our parking service was tested under a single service environment, in Chapter 5. If there are more than two services in the network, the content-based matching will

¹named-data.net

be more complicated. Especially, when service users cannot give a good description of interests, the system will have to adapt to all the different demands in order to provide the most suitable and useful information [269]. Some machine learning algorithms have aimed at improving the matching time and accuracy, for example, deep learning for information retrieval and multimodal interaction [270]. Thus, a multi-service network will be interesting to study, and also it can be an inception of NDN.

Fifth, to test urban service in a dynamically moving network, a real vehicle trace shall be adopted to simulate the intercontact time of any two vehicles. Yet, the real vehicle trace currently cannot adjust the waypoints according to the receipt messages. That is, we cannot have an application-aware vehicle trace [271]. If we try to modify the waypoints, we cannot make sure if the new waypoints are realistic enough. Hence, a mobility model which is extracted from real vehicle traces will be important for assessing the quality of the parking service proposed in Chapters 5 and 6. Moreover, with realistic vehicle traces, an incomplete-information data dissemination could be needed since drivers in urban areas are often volatile to change their directions and destinations. For example, the road oriented dissemination proposed by Cherif *et al.* [272].

Sixth, in Chapter 5, we assume the buffer of each car is unlimited. However, if the buffer size is limited, a cartography of information distribution will be different. We can then see the relationship between the information dissemination rate and the probability density of different types of information. That can help us to optimize our models in actions *a7* and *a8* while choosing a more realistic probability model.

Smart cities extract the idea of intelligent devices, and take advantage of team strength. It simplifies the tasks of each device and emphasizes the cooperation. Urban service can then thrive on it thanks to the popularity of massive sensor and infrastructure deployment. In a rapidly changing city, even more in a megacity, a new factor may appear and point out other network performance challenges. To sum up, our future works are mainly related to produce more experiences with more realistic datasets, especially network traffic models of different information flow and a reactive vehicle mobility, extracting from real vehicle trace.

Publication list

International Journal

- Trista Lin, Hervé Rivano and Frédéric Le Mouël, Urban Infrastructure Deployment for Wireless On-Street Parking Sensor Networks, *Procedia Engineering*, Elsevier, Volume 115, 2015, Pages 29-36, ISSN 1877-7058.

International Conference & Workshop

- Trista Lin, Hervé Rivano, Frédéric Le Mouël, Router Deployment of Streetside Parking Sensor Networks in Urban Areas, In *UM - Urban Modelling Symposium*. Oct 2014, Lyon, France.
- Trista Lin, Hervé Rivano, Frédéric Le Mouël, How to Choose the Relevant MAC Protocol for Wireless Smart Parking Urban Networks?. In the 11th ACM symposium on Performance evaluation of wireless ad hoc, sensor, & ubiquitous networks (PE-WASUN'14). Sep 2014. ACM, Montreal, Canada. Pages 1-8.
- Trista Lin, Hervé Rivano, Frédéric Le Mouël, Performance Comparison of Contention- and Schedule-based MAC Protocols in Urban Parking Sensor Networks. In the ACM international workshop on Wireless and mobile technologies for smart cities (WiMobCity'14). Aug 2014. ACM, Philadelphia, PA, USA, 1-8. Pages 39-48.

Preprint

- Trista Lin, Frédéric Le Mouël, Hervé Rivano, Crowdsourcing Continuous Location-Aware Update Service for Parking Assistance.
- Trista Lin, Hervé Rivano, Frédéric Le Mouël, Smart Parking: A Survey.

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