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Science Press Beijing

Springer

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ISBN 978-981-15-4568-9 ISBN 978-981-15-4569-6 (eBook)
https://doi.org/10.1007/978-981-15-4569-6

Jointly published with Science Press
The print edition is not for sale in China (Mainland). Customers from China (Mainland) please order the print book from: Science Press.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

The advanced methods of network mobile information services are the key points to support various information services. Human life is inseparable from these information services. Compared with the wired network environment, the current wireless mobile network environment is dynamic and uncertain. This brings many challenges from the data link layer to the application layer for the entire mobile information service methods and technical theories, such as the uncertainty problem brought about by neighbor discovery in networking, the instability problem in transmissions, the relationship mining between devices. Therefore, it is important to study the current supporting methods of network mobile information services and give related technologies for typical network mobile information service applications.

Mobile information service for networks can be defined as a platform-independent functional entity that provides various services based on the communication network platform. Mobile information service can be published on the network through various mobile devices. The services are represented in the form of various mobile applications.

This book mainly introduces the methods of mobile information service for networks. There are eight chapters in this book. First the book introduces the concept and the current development of mobile information service for networks. Then, the book introduces three main supporting technologies of mobile information service for networks. The technologies include the neighbor discovery technology in the data link layer, the routing and balanced association technology in the network layer, and the community structure detection technology in the application layer. Based on our mobile information service platform, this book introduces the development of related applications and the key technologies in the domains of intelligent transportation, smart tourism and mobile payment, such as trajectory analysis technology, location recommendation technology and mobile behavior authentication technology, which promote the development of mobile information service.

This book can be used as a reference for researchers in the field of computer science and technology, and also for researchers in the field of network mobile information service technology. The book includes lots of detailed and fundamental supporting technologies of mobile information service for networks. It shares many tips and insights into the development of related applications and the key technologies in the domains of intelligent transportation, smart tourism and mobile payment. It broadens the understanding of the real mobile information service platform in our project.

During the writing, we received many supports from Ph.D. students, postgraduate students of our research team. Thank you for providing relevant materials for this book.

Shanghai, China — Changjun Jiang
February 2020 — Zhong Li

Contents

Chapter 1
Preliminary of Mobile Information Service for Networks

Abstract With the rapid development of network technology, mobile information service for networks is an important part of people's lives. This chapter first describes the concept of mobile information service for networks and the general network architecture. Then this chapter introduces the classification of the mobile information services for networks, and finally lists the roles of key technologies in mobile information service for networks according to a hierarchical structure. In this book, network neighbor discovery technology, efficient network routing, user association technology, and network community detection technology will be elaborated later. After introducing these main technologies, this book will introduce mobile information service platform for networks and related applications in intelligent transportation, smart tourism, and mobile payment. Mobile information service for networks involves many techniques and methods. This book is only a summary of authors' recent innovative work about smart city. We hope that with the development of the times, new technologies will emerge continuously.

1.1 Concept and Development of Mobile Information Service for Networks

The rapid development of wireless network technology promotes extensive use of mobile devices such as mobile phones, tablets, and ultrabooks. The mobile network provides a solid platform for mobile nodes interconnections and applications of related services. To deal with various scenarios of human activities, information service based on the wireless mobile network has become a research hotspot.

We define **Mobile Information Service for Networks** as a platform-independent functional entity that provides various services based on the communication network platform. Mobile information services can be published on the network through various mobile devices in the method of wireless access networks [1]. With the development of 5G and Internet of Things, the carriers of mobile services not only include handheld devices but also include physical devices related to individuals, such as vehicles [2–4].

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https://doi.org/10.1007/978-981-15-4569-6_1

According to preliminary data released by App Annie, an app analytics company, the number of APP downloads exceeded 204 billion in 2019, an increase of 6% compared to last year. The total expenditure on paid applications, in-app purchases, etc., is $120 billion. Mobile users spend an average of 3.7 hours on APP each day. The explosive development has made mobile information services penetrate into every corner of people's lives.

There are many disciplines involved in mobile information service for networks. This book conducts a layered introduction to analyze related theoretical methods, and introduces new application technologies. Since the current mobile information service for networks is different from traditional information services, the requirements of adaptability of network changes, efficiency, security, accuracy, energy and sociality all bring about great challenges to its further developments.

1.2 Network Communication Architecture

According to the types of applications and communication standards, mobile information service for networks can be deployed under a centralized, distributed, or hybrid network communication architecture.

(1) Centralized Architecture (e.g. cellular networks): A centralized server can exchange, share, and transmit data between content providers and mobile users. In this client/server structure, the user is a client and the server provides contents such as maps, and videos. Under the centralized architecture, data is passed through third-party applications or service providers. This architecture is widely used in the network communications nowadays. The centralized communication architecture can not only provide information services efficiently and conveniently, but also can control the network globally. However, there are also some problems such as single point failure, privacy leakage [5].
(2) Distributed Architecture (e.g. networks supporting Ad hoc communication modes): Mobile users can directly establish P2P transmission links by using technologies such as Wi-Fi and Bluetooth. Under this architecture, nodes use the "storage-carry-forward" protocol to keep real-time communications in the physical world. Services based on this type of architecture are some location-based services [6], such as E-SmallTalker [7], MobiClique [8], Who's Near Me. The distributed architecture can be used as an effective way to reduce the transmission pressure of centralized base stations. However, the distributed architecture cannot be applied in large-scale areas.
(3) Hybrid Architecture: The centralized architecture is usually used by service providers while the distributed architecture has been promoting by the academic communities. A hybrid architecture can perfectly combine the domains of industry and academy together. In a hybrid architecture, a distributed network usually assists a centralized network to realize various services.

1.3 Classification of Mobile Information Service for Networks

Referring to the 2019 APP classification list given by Internet Weekly & eNet Research Institute, the content of mobile information service for networks includes the following 14 types: (1) Social welfare; (2) Government functions, such as party affairs, police affairs, taxation, citizen cloud, and labour unions; (3) Audio and video entertainment, such as video, live broadcast, games, music, and radio; (4) News such as books, and comics; (5) E-commerce platform (domestic or overseas); (6) Travel and transport, such as maps, taxis, tour, ticketing, accommodation, guides, and car rental; (7) Health care, such as body-building and medical treatment; (8) Social; (9) Financial management, such as banking, securities, insurance, stocks, investment, and management; (10) Automobile industry, such as charging of new energy vehicles and vehicle after sales service platform; (11) Learning and education; (12) Enterprise, such as mailbox, enterprise cooperation, customer relationship management, and financial affairs; (13) Utility tools, such as input method, wallpaper, browser, network security protection, search engines, weather forecast, application market, calendar, and transmission backup; (14) Leisures, such as beauty makeup, meal ordering, house lease, home furnishings, community service, job hunting, and express logistics.

In addition, the main external impacting factors of mobile information service for networks are the mobile environment and the individual. Therefore, the mobile information service modes can be divided into instant services, location-based services and personalized services [9] based on the three factors: time, location and individual.

The instant service mode can provide users with required information and services according to users' instant needs in a mobile environment. The instant information includes vehicles' security warning in Chap. 6, news, financial market, instant communications, etc.

The location-based service mode provides users with required geographic information and other information services related to the geographical location. These services are based on the geographical locations of users in a mobile environment. The location-based services include vehicle trajectory analysis in Chap. 6, location recommendations in Chap. 7, weather forecast, chatting and making friends, etc.

The personalized service mode can provide targeted information services for the personalized needs of users. And it can also establish an information demand model for users by utilizing a mobile information service system based on the privacy and identifiability of mobile terminals. The personalized services include personal payment authentications in Chap. 8, personalized location recommendation, personalized search and subscription services.

1.4 Key Technologies of Mobile Information Service for Networks

In this book, we will introduce some key technologies of mobile information service for networks according to a hierarchical structure and application backgrounds. To begin with, we mainly introduce the major technologies of mobile information service for networks in three layers:

- Neighbor discovery technology in the data link layer.
- Efficient network routing and balanced association technology in the network layer.
- Network community detection technology in the application layer.

Then, we will introduce some extension technologies for three main applications involved in a smart city, i.e., intelligent transportation, smart tourism, and mobile payment. The content structure of this book is shown in Fig. 1.1.

The key technologies and methods of mobile information service for networks include the following aspects:

(1) Neighbor discovery technology. In the mobile information service, neighbor discovery is an important technology in the data link layer. It is a technology that can discover neighbor nodes and establish effective connections. This technology guarantees the first step of the network building. High efficiency, energy-saving, and scene adaptation are problems encountered by the current technology. Therefore, for social application scenarios and crowded scenarios, this book presents a role-based neighbor discovery method and a crowded scenario-based neighbor discovery method, respectively. More details will be provided in Chap. 2.

(2) Efficient network routing and balanced association technology. In the network layer, the efficiency of various information services, depends on fast data transmissions. Traditional routing protocols that depend on the network topology or

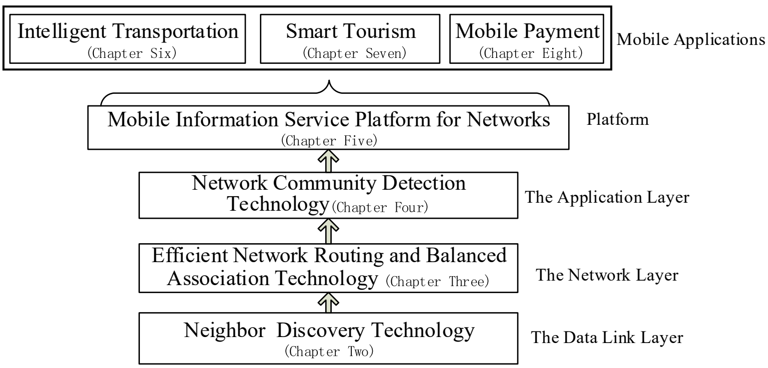

Fig. 1.1 Architecture of this book

simply depend on the encounter probability can no longer meet the requirements of efficient data transmissions. Therefore, for the multi-hop Ad hoc network, this book proposes a data forwarding algorithm LASS based on local activity and social similarity in slow mobile user network scenarios, and a cognitive routing protocol QCR in fast vehicle networking scenarios. Besides, for the centralized cellular network, the load balance of user associations is realized by utilizing spatio-temporal regularities of traffic flows based on reinforcement learning. More details will be provided in Chap. 3.

(3) Network community detection technology. In the application layer, the current mobile information service for networks is customized for individuals, therefore sociability is inherent in information services. Considering the different network communication architectures of mobile information services, this book explores new methods of community structure discovery and analyzes the relation between the underlying communication architecture and the top-level logical relationship network. In this part, we provide technical supports for recommendation algorithms, path planning and routing protocol design. More details will be provided in Chap. 4.

(4) Vehicle trajectory mining technology. After introducing the main technologies, this book details the current developments and latest technologies in the field of intelligent transportation. On the basis of previous work on the neighbor discovery technology in Chap. 2, this part focuses on analyzing the large data of vehicle trajectories in intelligent transportation. This part also solves the problem of accurate route estimation under sparse data and the problem of predicting vehicle behavior on the road based on coarse-grained GPS data. Vehicle trajectory mining technology can get rid of overdependence on hardware devices such as cameras, sensors and radar. Through analyzing historical data, drivers' driving habits can be extracted, and meanwhile, real-time warnings of driving behaviors can be realized by utilizing neighbor discovery wireless communication architectures. More details will be provided in Chap. 6.

(5) Personalized Location Recommendation Technology. This book details the current developments and latest technologies in the field of smart tourism. We mainly focus on location recommendation technology, because it is the basis of a series of issues in the application layer, such as tourism route selection, tourism product recommendation, traffic forecasting. To solve the problems of sparse check-in data and long tensor decomposition time in the location recommendation, this book presents a recommendation method which can accurately recommend locations and reduce computing time. This method is based on user social relationships in Chap. 4 and the similarities among users, time periods, and locations. In addition to the single-point location recommendation, a personalized location sequence recommendation is also provided in this book, which further enhances users' experiences of location services in smart tourism. More details will be provided in Chap. 7.

(6) Mobile payment authentication technology. This book details the current developments and latest technologies in the field of mobile payment. Based on our previous foundations in online transaction payments, this book focuses on

mobile terminals and analyzes the impact of user postures on gestures. This book presents a mobile authentication system architecture based on user gestures, and then introduces the model constructions and authentication methods of "login authentication" and "continuous authentication". More details will be provided in Chap. 8.

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Chapter 2
Technology of Neighbor Discovery for Networks

Abstract Neighbor discovery is one of the basic technologies of mobile information service for networks. It is the key to discover the surrounding nodes at the data link layer and organize the network effectively. Firstly, this chapter introduces the basic concept and the development of neighbor discovery in detail. According to popular social application scenarios, efficient neighbor discovery algorithms (Erupt and Centron) are introduced. In these algorithms, the Erupt algorithm divides the nodes into two categories according to their roles: the sponsor node and the participant node. Using a recession strategy, the sponsor consumes more energy in exchange for higher discovery efficiency. By creating a core group, the Centron algorithm solves the problem that communications between nodes will be affected by frequent collisions in the crowded region, which reduces the efficiency of discovery. The above algorithms are proved to be efficient in terms of energy, efficiency, and delay. Besides, these algorithms can provide inspirations for how to design better neighbor discovery algorithms in the future.

2.1 Introduction

Neighbor discovery refers to the process that the network node interacts with and discovers other nodes dynamically during the initialization [1, 2]. For example, some social applications [3–5], whose main application communication framework is centralized but its location-based sub-applications are distributed. Because the location of mobile nodes is uncertain, it is more challenging to build a distributed network architecture than a centralized one. Thus the node needs to adapt to dynamic changes of the network topology to discover neighbor nodes and establish an effective connection. Therefore, neighbor discovery algorithm serves as an important data link technology to accurately find neighbor in mobile information service for networks. Firstly, in this chapter, we simply review the mainstream methods of neighbor discovery. Then, aiming at daily social and crowded scenarios, this paper introduces a role based neighbor discovery method [6] and a crowded scenario based neighbor discovery method [7].

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https://doi.org/10.1007/978-981-15-4569-6_2

2.2 Related Work

The evolution of the neighbor discovery algorithm is mainly divided into three phases: synchronous, asynchronous, and derivative.

Most of the early neighbor discovery algorithms are embedded in the MAC protocol, such as S-MAC [8] and BMAC [9]. These algorithms mainly use the GPS of nodes or sending packets to synchronize the clock between two nodes. The work and sleep mechanisms between nodes are required to be consistent to achieve mutual discovery. However, these methods require redundant packets or power consumptions to maintain synchronization between nodes. Thus, These algorithms are difficult to implement in the mobile network for limited battery power supplies.

Later, McGlynn and Borbash separated the neighbor discovery algorithm from the MAC protocol for the first time and defined it as an independent protocol. They proposed an asynchronous neighbor discovery protocol called Birthday [10]. In Birthday, every node chooses whether it is working or not with a fixed probability in each timeslot. According to Birthday paradox, the node can discover each other through a random wake-up/sleep mechanism. Then, Vasudevan and others mapped the stochastic neighbor discovery to the classical stamp collector problem [11]. Through analizing of the efficiency of stochastic discovery strategy a Vasudevan et al. propsed more efficient strategy. However, a fatal drawback of the stochastic neighbor discovery strategy is that there is no upper bound for the time delay of discovery. That is, two nodes may never find each other.

In order to solve this problem, scholars have proposed a deterministic asynchronous neighbor discovery algorithm. The deterministic neighbor discovery algorithm is mainly divided into two types. One is the quorum-based algorithm [12, 13], and the other is the prime-based algorithm [14, 15]. The quorum-based algorithm divides time into a two-dimensional square matrix. Each node randomly chooses one row and one column as active slots. The discovery will occur when a pair of two nodes has at least two active slots overlapped. However, if two nodes are in different duty cycles, the time of two nodes cannot be divided into two square matrices of the same size. Then it is difficult for the quorum-based algorithm to achieve good discovery results. To solve this problem, Sangil Choi and others designed a protocol called BAND which used combinatorial theory. To a certain extent, BAND has improved the discovery delay bound and energy consumption of the quorum-based algorithm. The prime-based algorithm is mainly designed according to Chinese Remainder Theorem [16], among which Disco [17], U-connect [18] and Searchlight are the main representatives. In Disco, each node chooses a set of unequal prime numbers. When the sequence number of the timeslot is divisible by any of its prime numbers, the node turns into active state. U-connect proposes an inner product matrix of energy and delay so that each node only needs to select one prime number. This can improve discovery efficiency and ensure that the energy consumption of nodes is similar to Disco. Compared with the stochastic algorithm, Disco and U-connect have the upper bound of discovery delay, but the average delay doesn't perform as well as the stochastic algorithm. Searchlight makes some adjustments under symmetrical conditions. Searchlight mainly utilizes the rule that the offset between the working cycle is the same when they have the same duty cycle. In order to improve the average discovery efficiency, Searchlight designs a timeslot with two working states: anchor and probe. BlindDate is an improvement to Searchlight, the main purpose is to reduce the upper bound of the discovery delay.

However, it is difficult to improve the discovery efficiency in an asymmetric situation (nodes have different duty cycles) for the prime-based algorithm. Zhang and others [19] proposed an accelerated middleware based on demand change, called Acc. The main idea of Acc is to analyze the discovery relationship between direct and indirect neighbors of nodes on the basis of Disco. Acc adds some working timeslots in each cycle to achieve acceleration. Sun [20] proposed a unified framework called Hello to include all deterministic asynchronous neighbor discovery algorithms (e.g., Quorum, Disco, U-connect, and Searchlight). The Hello framework effectively reduces the discovery delay, but the energy consumption of the node is not taken into account.

The above neighbor discovery algorithm in asynchronous phases is mainly composed of stochastic algorithms and deterministic algorithms. After that, the neighbor discovery algorithm enters the derivative phase. In the derivative phase, the researchers mainly consider the influence of different factors on the discovery algorithm. Chen [21] focused on the effect of the neighbor discovery algorithm when the number of timeslots is not positive and the length of the timeslot is inconsistent. Then Chen proposed a non-integer neighbor discovery algorithm. Meng [22] combined this idea with the Searchlight algorithm to propose (A)Diff-Code neighbor discovery algorithm. (A)Diff-Code utilizes the encoding strategy algorithm based on non-integer to improve discovery efficiency when the number of timeslots is non-integer. Other researchers consider the efficiency of neighbor discovery in the case of multi-channel [23], multi-hop [24], multi-sending and receiving packets [25]. Combining four routing mechanisms in mobile ad hoc networks. In addition, some researchers have introduced neighbor discovery into multi-directional antenna environment [26, 27], multi-user environment [28], and cognitive network environment [29].

2.3 Role-Based Neighbor Discovery Algorithm

Recently, a lot of location-based social applications been developed to attract local individual users such as StreetPass and Vita. These applications require that nearby participants can be connected efficiently (low-latency and energy-efficient) in a limited time. The process of discovering and connecting such nodes is called neighbor discovery. Most of the existing neighbor discovery algorithms regard the nodes as the same roles. In fact, the role of nodes can be divided into active and passive in neighbor discovery. In this chapter, we mainly introduce a role-based neighbor discovery algorithm named Erupt. To achieve efficient neighbor discovery, Erupt distinguished active and passive roles and assign different discovery strategies to nodes with different role. Before introducing the role-based neighbor discovery, the wireless network model and assumptions are given.

2.3.1 Wireless Network Model and Assumptions

Node: We assume that N denotes the total number of nodes in the network. Each node has its unique ID(e.g. MAC address) so it can be distinguished from others. Each node is equipped with a radio transceiver that allows a node to transmit or receive messages asynchronously.

Neighbor: Two nodes become neighbor through neighbor discovery if and only if one node transmits message and the other one listens. When the transmission node has received the listening node's feedback, the two nodes become neighbor.

State: A node can be in one of three states: transmit, listening, or sleeping. A node in transmit state broadcasts a discovery message advertising itself to establish a connection with the surrounding nodes. A node which in listening state listens for discovery message. If such a message is heard, the node will feedback to the source address of the message through the listening channel. A node in sleeping state is neither broadcasting nor listening.

Role: In this section, two roles are defined for a node: the sponsor(SP) and the participant(PA). The sponsor node is either in transmit state or sleeping state. In contrast, the participant node is either in listening state or sleeping state and will not in transmit state.

Time: Time is divided into discrete timeslots. We let t denote the time cycle. The size of time cycle is determined by the duty cycle. The duty cycle is defined as the ratio of transmit or listen period to a complete cycle of a node. In addition, the working cycle can be used to define the sponsor node, which can be expressed as I. The expression of I is as follows:

$$I = t \cdot [(t/2)] \tag{2.1}$$

Note that t represents a time period.

Energy: Define energy consumption of a node is zero when a node is in sleeping state. When a node is in transmit state or listening state, we assume the energy consumption is the same in a timeslot, and we assume that it is 1.

2.3.2 Description of Erupt Algorithm

When some nodes start mobile social application, they will actively initiate neighbor detection. In other words, behind every neighbor discovery process, there is an initiative node called the sponsor. Therefore, mobile nodes in the network are divided into active and passive nodes. Passive nodes are called the participant. We find a common phenomenon that the sponsor will spend more energy to invite more devices to join the applications as soon as possible. When a sponsor does this, energy consumption in the network will show explosive growth. The ERUPT neighbor discovery algorithm is designed based on the above analysis, as is shown in Algorithm 2.1.

Algorithm 2.1 Erupt Algorithmic

```
if a node is in SP mode then
  k = 1
  for i from 1 to I do
    when i%k ≡ 1 , the node is in working state
    if i%⌊(t/2)⌋ = 0 then
      k = k + 1
    end if
  end for
else
  Randomly select number a, b from (1,⌊(t/2)⌋) and (⌈(t/2)⌉,t)
  for i from 1 to t do
    if i%a = 0 or i%b = 0 then
      the node is in working state
    end if
  end for
end if
```

In Algorithm 2.1, when a node is in SP mode, we name it sponsor node. The sponsor node has a working cycle I, which is divided into all-out part and recession part. The sponsor node in the all-out part is always in transmit state, and the duration is a time cycle t.

The recession part is from the second time cycle to $\lfloor t/\lfloor t/2 \rfloor \rfloor$th. In recession part, a rule that the sponsor node broadcasts message when $t \equiv 1(mod\, k)$ will be followed, where k is the serial number of current time cycle t of I. When a node is in PA mode, we name it participant node. It divides its time cycle into two parts. The former consists of $\lfloor (t/2) \rfloor$ timeslots, the latter consists of $\lceil (t/2) \rceil$ timeslots.

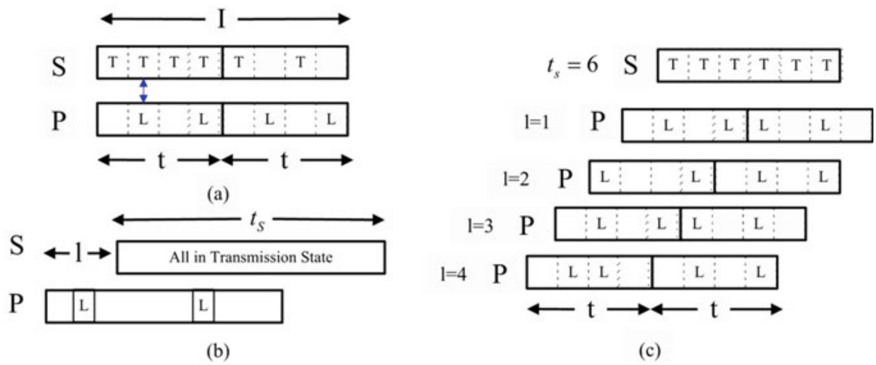

Fig. 2.1 The offset between the participant node and the sponsor node

Then the participant node randomly chooses one timeslot in listening state in each part and in sleeping state of the other timeslots.

2.3.3 Analysis of Two-Node Case

In this section, we will discuss the case where there are a sponsor node and a participant node in the network. In the two-node network, the discovery occurs when a node is in transmitting state and the other is in listening state. We define the two nodes S and P respectively. Node S is in the sponsor role, and node P is in the participant role. An example is shown in Fig. 2.1, the time cycle t of node S and P are set to 4. We let t_S denote the time cycle of node S and let t_P denote that of node P. I is the time difference between node S and P in the working cycle, which is composed of several time slots.

We analyze the ERUPT algorithm from two aspects. First, we investigate the average time it takes a sponsor to discover a neighbor. Here, such an average time is called the average latency. Second, we will show the duty cycle and energy consumption of the sponsor node and the participant node.

In Fig. 2.1a, node S is the sponsor node and node P is the participant node when time cycle $t = 4$. Figure 2.1b shows the offset between the time cycle of the participant node P to the sponsor node S while the sponsor node S starts its working cycle. Figure 2.1c shows the cases of different possible offsets, where $t_S = 6$, $t_P = 4$.

2.3.4 Average Latency

In this section, we discuss average neighbor discovery latency of the two-node case in ERUPT algorithm from two situations: $t_S \geqslant t_P$ and $t_S < t_P$.

Lemma 2.1 As shown in Fig. 2.1c, the offset l between the time cycle of the participant node P and the sponsor node S satisfies $l \in 0, 1, 2, \cdots, t_P - 1$.

We first discuss the case when $t_S \geqslant t_P$.

Lemma 2.2 When $t_S \geqslant t_P$, the discovery will occur in the all-out part of the sponsor node S in Fig. 2.1c.

Proof Based on the description of the sponsor node in the previous section, when node S starts its working cycle, it will broadcast messages in all timeslots in its all-out part. In Lemma 2.1, we know while node S begins to broadcast message l, which can be anyone in $\{0, 1, 2, \cdots, t_P - 1\}$. Whatever l is, t_S will contain one part of the participant node P (see Fig. 2.1c). Based on the description of the participant node, node P will randomly select a time slot in each part in listening state. So the sponsor node S will discover node P in its all-out part.

Theorem 2.1 When $t_S \geqslant t_P$, the average latency of node S discovering node P is almost $7t_P \big/ 24 + 1 \big/ 2$.

Proof We assume the probability of $l \in \{0, 1, 2, \cdots, t_P - 1\}$ is the same. We introduce $k = \lceil t_P \big/ 2 \rceil$. When t_p is even, $t_P = 2k$. We calculate the expectation by dividing l into $0 \leq l < k$ and $k \leqslant l < 2k$ two cases, then put them together. We get the average latency is $\frac{7k^2+6k-1}{12k} \approx \frac{7t_P}{24} + \frac{1}{2}$. When t_P is odd, $t_P = 2k - 1$. Similar to the case $t_P = 2k$, we get the average latency is $\frac{7k^2-k-2}{12k-6} \approx \frac{7t_P}{24} + \frac{1}{2}$. So the average latency of node S discovering node P is almost $\frac{7t_P}{24} + \frac{1}{2}$.

In the case $t_S \leqslant t_P$, the sponsor node S may not discover the participant node P if t_P is large enough. So we will discuss the relationship between the discoverable probability and the choice of t_S in this case. First, we give an assumption to support our analysis. We assume $d_{SP} = t_P = t_S$, where d_{SP} denotes the difference of the time cycle between node S and node P. Then we let P_1 and P_2 denote the two parts in the time cycle of the participant node P. We have $P_1 = \lfloor t_P \big/ 2 \rfloor$, $P_2 = \lceil t_P \big/ 2 \rceil$ and $t_P = P_1 + P_2$. At last, we use p_{SP} to denote the discoverable probability and $p_{SP} = p_h + p_t$. Where p_h denotes the probability that the discovery occurs in the all-out part of the working cycle, and p_t denotes that in the recession part.

Theorem 2.2 The average value of p_h approaches $\frac{17}{24}$.

Proof We first discuss the case $1 \leqslant d_{SP} \leqslant P_1$. (i.e., $t_S < t_P \leqslant 2t_S$). There are four cases of l (Fig. 2.2a–d)). We calculate the expectation of l and use Pd_{SP} to denote it. Then we get the expectation of d_{SP} based on Pd_{SP}. So we have

$$p_h = \sum_{d_{SP}=1}^{P_1} p_{d_{SP}} = \sum_{d_{SP}=1}^{P_1} \left(1 - \frac{d_{SP}^3 - d_{SP}}{3P_1 P_2 (P_{1+} P_2)}\right) \approx \frac{23}{24} \tag{2.2}$$

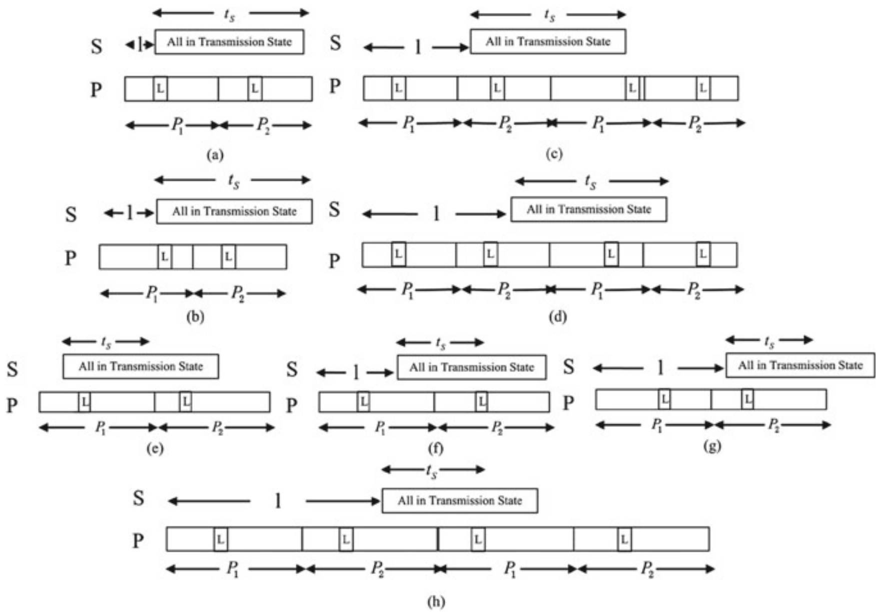

Fig. 2.2 Discovery probability of d_{SP} under different cases

Then we consider the case $P_1 + 1 \leqslant d_{SP} \leqslant P_1 + P_2 - 1$. It's equal to $t_P > 2t_S$. There are still four cases of l (Fig. 2.2e–h). We get the value of p_h under this case is

$$p_h = \sum_{d_{SP}=P_1+1}^{P_1+P_2-1} p_{d_{SP}} = \sum_{d_{SP}=P_1+1}^{P_1+P_2-1} \{1 + \frac{1}{3P_1P_2(P_1+P_2)}[d_{SP}^3 - (3P_1+3P_2)d_{SP}^2$$
$$+\left(3P_1^2 + 3P_2^2 - 1\right)d_{SP} - P_1^3 - P_2^3 + P_1 + P_2]\} \approx \frac{11}{24} \tag{2.3}$$

We combine Eqs. (2.2) and (2.3), and we get $p_h = \frac{17}{24}$.

Figure 2.2a–d shows four cases of l when $1 \leqslant d_{SP} \leqslant P_1$. Figure 2.2a shows the case $1 \leqslant l \leqslant d_{SP} - 1$ and the discovery probability is $1 - \frac{l}{P_1P_2}(d_{SP} - l)$. Figure 2.2b shows the case $d_{SP} \leqslant l \leqslant P_1$ and the discovery probability is 1. Figure 2.2c shows the case $P_1 + 1 \leqslant l \leqslant d_{SP} + P_1 - 1$ and the discovery probability is $1 - \frac{l-P_1}{P_1P_2}[d_{SP} - (l - P_1)]$. Figure 2.2d shows the case $d_{SP} + P_1 \leqslant l \leqslant P_1 + P_2$ and the discovery probability is 1. Figure 2.2e–h shows four cases of l when $P_1 + 1 \leqslant d_{SP} \leqslant P_1 + P_2 - 1$. Figure 2.2e shows the case $1 \leqslant l \leqslant P_1 - t_S$ and the discovery probability is $\frac{P_1+P_2-d_{SP}}{P_1}$. Figure 2.2f shows the case $P_1 - t_S + 1 \leqslant l \leqslant P_1$ and the discovery probability is $1 - \frac{l}{P_1P_2}(d_{SP} - l)$ Fig. 2.2g shows the case $P_1 + 1 \leqslant l \leqslant d_{SP}$. Figure 2.2h shows the case $d_{SP} + 1 \leqslant l \leqslant P_1 + P_2$ and the probability is $1 - \frac{l-P_1}{P_1P_2}[d_{SP} - (l - P_1)]$. Since p_t is hard to get the formula, we get it through experiments by using mathematical simulation tool. When $1 \leqslant d_{SP} \leqslant P_1$, $p_t \approx 0.0487$. When $P_1 + 1 \leqslant d_{SP} \leqslant P_1 + P_2 - 1$,

$p_t \approx 0.2555$. When $1 \leqslant d_{SP} \leqslant P_1 + P_2 - 1$, $p_t \approx 0.1440$. Obviously, even when the duty cycle of nodes is very low, sponsor nodes still have a certain probability to discover participant nodes.

2.3.5 Duty Cycle and Energy Consumption

Based on our assumption in Sect. 2.3.1, the energy consumption problem becomes the number of timeslots of a node in transmit state or listening state. We use E to denote the energy consumption and use DC to denote the duty cycle. In this section, we will discuss the energy consumption of the sponsor node S.

Theorem 2.3 The energy consumption in the working cycle of the sponsor node S is $E_S = \sum_{i=1}^{k} \lceil t_S / i \rceil$, and the duty cycle is $\frac{\sum_{i=1}^{\lfloor t_S/2 \rfloor} \lceil t_S/i \rceil}{t_S \cdot \lfloor t_S/2 \rfloor}$, where $k = \lfloor t_S / 2 \rfloor$.

Proof Based on the description of Erupt algorithm, the node S will broadcast messages in all timeslots in the working cycle. In recession part, node S will broadcast messages $\lceil t_S/2 \rceil$ timeslots in the second time cycle, and $\lceil t_S/3 \rceil$ timeslots in the third and go on by the same analogy until the $\lceil t_S/2 \rceil$th time cycle ends. The energy consumption of all time cycles in the working cycle of the node S is

$$E_S = t_S + \left\lceil \frac{t_S}{2} \right\rceil + \cdots + \left\lceil \frac{t_S}{\lfloor t_S/2 \rfloor} \right\rceil = \sum_{i=1}^{\lfloor t_S/2 \rfloor} \lceil t_S/i \rceil \tag{2.4}$$

We can get the duty cycle of node S is, $\mathrm{DC}_S = \frac{E_S}{I_S} = \frac{\sum_{i=1}^{\lfloor t_S/2 \rfloor} \lceil t_S/i \rceil}{t_S \cdot \lfloor t_S/2 \rfloor}$.

2.3.6 Analysis of the Multi-node Case

In this section, we will discuss the case where there are more than two nodes in the network. We assume the sponsor node is n_S, and the other $N - 1$ nodes are $n_1, n_2, \cdots, n_{N-1}$. We will analyze our algorithm from the simple case and the real case. In the simple case, each node has the same time cycle and the participant nodes have the same duty cycle. The real case means each node has its own time cycle. When two nodes or more than two nodes broadcast messages at the same time, a collision will occur. In this section, we do not consider this case that there are two or more nodes in sponsor mode in the network.