Performance Analysis of Network Assisted Neighbor Discovery Algorithms

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Abstract

Recently there has been an increasing interest in applications that enable users in the proximity of one another to share experiences, discover surrounding events, play online games and in general develop proximity based social networks. Most of the existing applications are based on cellular network communications, combined with over-the-top (OTT) solutions involving either registration at an application server and/or obtaining location information from a positioning system such as Global Positioning System (GPS). However, registration at a server often requires continuous registration updates due to, for example, mobility and changes in user population, which is a tedious and resource consuming process. In addition, using GPS drains the battery of devices.

Since the spectrum used for cellular network is limited, it can become a scarce resource with increasing quantity of the devices. In order to deal with these problems, the concept of direct Device-to-Device (D2D) communication has been proposed as a solution. Using D2D technology, devices can discover nearby devices without extra positioning information. It can not only increase the spectrum efficiency, but also improve the coverage of cellular network. The discovery of devices can be prepared before the actual communication phase or proceed simultaneously. In this work, we mainly investigate the former one, which is called a-priori discovery. In fact, a-priory device discovery provides a value on its own right, independently of a subsequent communication phase using D2D or traditional cellular communication.

Previous studies indicate that ad hoc D2D discovery (i.e. without cellular network assistance) is feasible but time, resource and energy consuming. Recognizing this problem, both academia and industry pay more attention to the D2D discovery in cellular spectrum, where D2D discovery can be assisted by a cellular radio access network. Despite this interest, to the best of our knowledge, there is essentially no work on identifying different degrees of network assistance (that we call the “network assistance levels”) and evaluating the potential gains of specific network assistance algorithms.

Therefore, in this thesis work we develop algorithms that take advantage of network assistance to improve the performance of the ad hoc neighbor discovery algorithms in terms of energy efficiency, resource utilization, discovery time and discovery rate. To address the requirements of different applications and types of devices, two design objectives are studied in this work. The first one is discovery time prioritized without energy limitation, while the other is constrained to using a certain amount of energy. We distinguish five levels of network involvement from allowing for synchronization to explicitly providing information on the used peer discovery resources. The analysis in this work indicates that the setting of transmission probability for devices, which depends on system load, plays a critical role in the process of D2D discovery. Furthermore, stopping the devices which have already been discovered by enough candidates can improve the performance, in terms of reducing the interference to other devices and saving energy consumption. It is also shown in the simulation results that, to reach a given quantity of D2D communication candidates for all the devices in the area of study, the discovery time as well as the energy consumption can be reduced up to 87-91% from the lowest level of the network assistance to the highest level.
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1. Introduction

1.1. Background

One of the most significant current discussions in wireless communication is the applications based on proximal location of users to share experiences, discover surrounding events, and play online games. In most of these existing applications, the devices in vicinity still have to communicate through cellular network rather than set up connection directly, for instance Foursquare and Glancee. Foursquare requires registration of devices to different small regions, and the devices within the same registered range can use the service together. However, the devices need to register constantly due to moving of users, which is a signal and energy consuming procedure. In contrast, Glancee does not require registration of devices, instead of which they discover the devices in proximity based on the GPS information [1], but questions are raised that battery of devices drains in using GPS and GPS is not reliable indoors. Moreover, as various devices becoming smarter and increasingly pervasive, more and more devices of different types can be carried simultaneously by one user [2], so the resource of cellular network will be exhausted with this trend sooner or later. To solve these potential problems and take advantage of the proximity of devices, the concept of direct Device-to-Device (D2D) communication is proposed as a solution. Consequently, we can benefit from this new type of communication by not only increasing the spectrum efficiency, but also improving the coverage of the cellular network [3].

A fundamental design question for D2D communication is the device (peer) discovery, and the devices can discover potential candidates and establish direct connection automatically. If the discovery phase and communication phase take place simultaneously, we call it \textit{a-posteriori} discovery, while device (peer) discovery is the precondition for D2D communication in so called \textit{a-priori} discovery. We focus on \textit{a-priori} discovery in this work.

The studies in the past have shown that D2D discovery without the assistance of network is feasible [4],[5],[6], but it costs much time and energy. Thus growing attention is drawn in D2D communications in cellular spectrum, where D2D discovery can be assisted by the cellular infrastructure [3],[7].

Network Assisted D2D Communications is of interest for 3GPP R12 recently. Compared with Bluetooth [6] and Wi-Fi Direct, network assisted D2D discovery can benefit from the cellular network in both the discovery phase and communication phase, and the use of licensed bandwidth can effectively reduce the unexpected interference. There are some examples for the existing well-known D2D communication systems. The Nokia Instant Community (NIC) is based on Wi-Fi technology, which is presented in [7],[8]. They design a beacon opportunity frame structure, and define different states for the devices. The multi-hop communication is supported in NIC, which can obviously increase the range of the network, but both of the latency and data rate become new challenges for it. Particularly, the NIC can benefit from the Wi-Fi network to transfer large packets when it is available. The FlashLinq is recently proposed by Qualcomm as a
D2D communication system, and they have a good mechanism for devices to discovery their neighbors in a large range with high efficiency. However, the cellular network only assists with synchronization in FlashLinq [4],[9] and the performance in the discovery phase can be improved if more assistance is provided by the cellular network. The wireless sensor network (WSN) is an ad hoc network, which is composed with numerous distributed devices. Through the connection between the devices, the entire network is set up. The algorithms revealed in [5] indicate that it can benefit from the availability of the number of neighbor nodes and the collision detection in the network initialization. However, it is not easy for the devices to have updated information about the number of their neighbors in such a network.

To our best knowledge, this work is the first to focus on the role of cellular network and distinguish the cellular network assistance into five levels in network assisted D2D discovery.

1.2. Purpose and Scope

The study item for D2D discovery and communication in 3GPP is to study use cases and identify potential requirements for an operator network controlled discovery and communication between proximate devices. It works under continuous network control and 3GPP network coverage, for commercial or social use, network offloading, public safety, integration of current infrastructure services and so forth. [10]

As described in [3], a-priori discovery allows discovery of devices before the actual communication phase, while in a-posteriori discovery, devices detect the others in proximity which have started to communicate. In this work, we focus on the a-priori method, since it is more suitable for a range of D2D applications.

The purpose of this thesis work is to indicate the role of network in the phase of D2D discovery and to identify the potential gain which can be obtained with different degrees of network assistance.

The study of this work is based on the cellular network of LTE-A in an urban area. From the perspective of energy consumption, one type of devices is strictly constrained by the budget of energy (e.g. wireless sensor), while another type of device requires a quick discovery time more than the energy consumption (e.g. laptop). In reality, the objectives are determined by both the preference of users and battery life. Thus both time priority discovery and energy limited discovery are investigated in this work.

Particularly, referring to what are needed from the network and complexity of them, we like to study the network assistance from the following 5 levels from low to high.

- Synchronizing and broadcasting available resource to all devices (Level 0)
- Broadcasting the available resource and the number of devices which want to be discovered in the study area in the beginning (Level 1)
- Broadcasting the available resource and the number of devices which want to discover others and the ones want to be discovered by others in the study area in the beginning (Level 2)
• Broadcasting the available resource and the number of devices which want to discover others in the study area in the beginning and the number of devices want to be discovered by others continuously (Level 3)
• Unicasting the available resource to devices (Level 4)

We employ different algorithms to the scenarios with different level of network assistance, so another main task of this work is to look for the optimal algorithm and proper parameter configuration related to various scenarios. In order to make the work feasible to implement in reality, the resources for peer discovery are all mapped into the LTE frame structure.

1.3. Thesis Structure

The thesis is divided into eight chapters. In Chapter 2, the basics and principles of D2D communication are introduced. Chapter 3 gives a brief discussion on the feature of similar systems, and then compares the ad hoc discovery with cellular network assisted discovery. The simulation model and some elements related to this work are described in Chapter 4. Then the solution approaches are explained in Chapter 5. In Chapter 6, the numerical results and analysis are presented. Finally, the conclusions are drawn in Chapter 7 and the future work is given in the last chapter.
2. Network Assisted D2D Communication in LTE-Advanced

2.1. Concept of D2D Communication

D2D communication is an option for the UE devices (or other types of devices) in proximity to communicate directly rather than via eNB, which can increase the spectrum efficiency, reduce the latency and lower the energy consumption for both UEs and eNBs.

The direct D2D communication uses the uplink channels of the cellular network to transmit beacon and paging signals. In the traditional cellular communication, both of the devices need a pair of channels to communicate with eNB. However, if the direct D2D communication is achievable, then only one pair of channels is needed. In this way, the usage of the resource can be doubled with D2D communication without adding more cost.

Previously, the unexpected interference cannot be controlled when the D2D communication uses unlicensed bandwidth, such as Wi-Fi Direct and Bluetooth. The new concept of D2D communication works in the licensed bandwidth, which can be assisted by the cellular network, thereby saving both time consumption and energy consumption. It is possible and can be advantageous that the D2D communication use the same bandwidth as the cellular network, unless a new bandwidth is set specifically for D2D communication. However, if the D2D communication uses the same bandwidth as the cellular network, the interference between the D2D link and the cellular network cannot be neglected. The influence of this new type of intra-cell and inter-cell inference is analyzed in [3], [11], [12]. If a certain bandwidth of spectrum can be set apart specifically for D2D communication, both the cellular network and D2D communication could survive from this kind of interference.

We design a frame structure for D2D communication based on the LTE-A system in the modeling section as working assumptions, hoping to present an example for the case that D2D and cellular communication can cooperate efficiently. Many of the other design aspects of D2D communication can be found from [3], which states the power control and SINR target affect much on the performance of the D2D communication.

Even though D2D communication has its advantages for the devices in vicinity, it is not always necessary to use D2D communication instead of cellular network communication. The load of the cellular network and how far they are away from the eNB also play key roles in selecting which one to use, and the network can help with the mode selection. [13]

2.2. D2D Discovery Phase and Communication Phase

In cellular system, the UEs exchange signaling with eNBs periodically, even they are not enjoying the services from the network at the moment. In this way, there are always weak
connections between the UEs and eNBs, and they can set up a connection immediately when there is a need for that. On contrary, there is no such a connection between the devices, so they need to discover their neighbors which meet the requirement of starting D2D communication directly. From this perspective, the procedure of D2D communication can be divided into two phases, which are discovery phase and communication phase, and the discovery phase is the prerequisite for the communication phase. In the discovery phase, which is to some extent similar to the cell search procedure in LTE-A system before actual communication [13], the devices search for the potential candidates in proximity which is preparing to set up D2D communication, while in the communication phase, the devices establish connections directly to use applications based on D2D communication.

Obviously, the following issues seem to be nontrivial for the D2D discovery. Firstly, the quantity of its neighbor candidates is important for one device in the D2D communication, as more candidates can increase the probability of finding a suitable candidate to start the D2D communication. Secondly, it is very friendly if the discovery could be finished within a short time. Last but not least, the energy consumption of the device should be kept under a low level. Therefore, we use these parameters to evaluate the procedure of D2D discovery.

As mentioned previously, there are two types of discovery, including *a-priori* discovery and *a-posteriori* discovery, and we focus on *a-priori* discovery in this work, because it can be used without requiring that the devices have started a communication session prior to proximity detection. In fact, *a-priori* discovery provides a value on its own right and can stimulate communication scenarios in which devices in the proximity of each other communicate explicitly on the bases of a common location perhaps without knowing each other.

There are many factors affect the performance in *a-priori* discovery. At first, if the transmission power is set to a higher level, the coverage of the given device can be increased, which indicates more candidates might be discovered. Nevertheless, more energy is consumed with higher transmission power, which should be constrained by the energy budget of the device. Also, higher power leads to increasing interference levels that might adversely affect the discovery process. Next, although more resource used for peer discovery can always save the discovery time, the frequency spectrum is limited, which means we must use it in an effective way. The most important one which affects much on the D2D communication is the probability for devices to transmit its beacon signals on overlapping time and frequency resources, which is closely related to the load of the system. Frequent transmitting can contribute to finish discovery fast, but it also lead to more interference between the devices, which deprave the quality of the SINR or even induce failure. In this sense, the entire discovery time and energy consumption depend heavily on the setting of this probability and selecting the beacon transmission resources.

On the whole, the factors discussed above can influence the performance of D2D discovery much, which are also the keys the network can assist with. Since the transmission power should be set according to the total energy budget and the amount of resource for device discovery is limited by the available spectrum, the most executive parameter the network can assist with is the transmission probability. We have mentioned that the setting of transmission probability depends on the load of the system, so the network can assist with the knowledge on the number of registered devices of different types and available resources, which give rise to the distinction of possible network involvement.
2.3. Why the Network Assistance is Needed

In D2D communication, the devices can decide power setting and transmission probability by themselves. However, it does not mean that the network stops playing any role in D2D communication.

From the perspective of users, there is no doubt that all of them want to be discovered fast by more neighbors with least energy consumption. Although the D2D discovery in the absence of network assistance is still feasible, it is a time-consuming and energy-consuming procedure. In fact, if there is no organizing from the cellular networks, the devices can hardly discover expected number of their neighbors in a high load system. Without knowledge on the load of the system, it is very difficult for the devices to set the transmission probability properly, which lead to the low efficiency of the entire system. Conversely, the cellular network can help with synchronization and knowledge on the load of the system, which can make the process of discovery well organized.

Additionally, if the design of D2D communication is based on the LTE-A system, there will be no need for it to create new design for the structure of the PHY/MAC layer [13]. Moreover, it is easy for the network to manage the security of the communications [16].
3. D2D Discovery in Ad Hoc and Cellular Networks

The D2D discovery has advantages and drawbacks in both ad hoc and cellular networks. In ad hoc system, the mechanism is simple, but the performance is not as good as in cellular network. In this chapter we compare the features and functions between different systems in both ad hoc and cellular networks.

3.1. Wi-Fi Direct and Bluetooth

Both Wi-Fi and Bluetooth are mature techniques which are widely used at present. More recently, the Wi-Fi Direct based on the Wi-Fi techniques is proposed for D2D communication. The network structures for both Wi-Fi Direct and Bluetooth are ad hoc, which means the nodes in the network are adaptive and self-organizing without control from the network center.

The Wi-Fi networks can provide guaranteed and high data rate connectivity to the devices with radio technologies IEEE 802.11. They work in the unlicensed 2.4 GHz and 5 GHz radio bandwidth. The Wi-Fi Direct is based on the technique of Wi-Fi, which can connect devices with Wi-Fi Certified mark directly without joining in a general Wi-Fi network. [14]

It is very convenient to share information and enjoy online services with Wi-Fi Direct devices. A user can view the list of candidate devices and invite (or being invited by) other devices, and all the things like transferring files and playing online games, which have to be completed via local network in the past, are easy to be achieved even without a local Wi-Fi network. [14] However, because of the power limit, the coverage of Wi-Fi device is very small, and the sustained transmitting and scanning in the discovery phase drain the battery.

Similarly as Wi-Fi, Bluetooth also works in the unlicensed 2.4 GHz frequency bandwidth. Normally, the Bluetooth devices can act as one of two different roles in the discovery phase. One type of them transmits beacons and listens to replies, while the other devices scan for beacons and send responses. The roles of the Bluetooth devices are not immutable, and the residence time to act as a given role is random, in case that one pair of devices which are always in the same role cannot discover forever.

One of the typical application occasions for Bluetooth is that two users with mobile devices can transfer information when they are in vicinity. Generally, the data rate of Bluetooth can reach up to 1 Mbps, but the distance between the users have to be kept within a small range. Furthermore, although the power level for Bluetooth is low, the periodic or continuous scanning may also consume considerable energy. [15]

In summary, both Wi-Fi Direct and Bluetooth work in an unlicensed bandwidth, which are subject to the unexpected interference. Without the synchronization, the energy consumption for
device discovery is exhausted and the efficiency is very low as well. Moreover, the transmission power is quite low in both systems, so the coverage of the devices and the number of neighbors they can discover are very limited.

### 3.2. Wireless Sensor Networks

Wireless sensor network (WSN) is a typical ad hoc wireless network, aims at establishing a whole network for all its sensors to connect each other. It can work in several frequency bands, including 315 MHz, 433 MHz and 2.4 GHz. The information gathered by the nodes are transferred to the center of WSN via many hops, so the nodes act as both information makers and relays in WSN. Before serving in a network, a new node has to discover and be discovered by some neighbors in the existed network to become one part of it. Normally, the discovery cannot obtain assistance from its center or the infrastructure of cellular network, but in some cases, a global clock can provide synchronization to the nodes.

Several algorithms for the neighbor discovery for the ad hoc wireless network are stated in [5]. Since the techniques for WSN are relative mature, the algorithms for device discovery in WSN can also be used as reference to the D2D communications with cellular network. In their algorithms, they assume a collision detection to distinguish the situation of collision and idle, and the devices are able to obtain the knowledge on whether they have been successfully discovered by others.

The performance and time complexity of their algorithms for neighbor discovery according to the scenarios with/without collision detection and with/without synchronization are presented in [5]. In synchronous scenario, the discovery time follows \( ne(\ln n + c) \) without collision detection, which is similar as the coupon collection problem, while time complexity is equal to \( o(n) \) with collision detection. Moreover, they claim that the discovery time is doubled in the asynchronous scenario, compared with the synchronous scenario.

Additionally, the battery for the sensors is not changeable after deployed, so the energy consumption is a serious problem. Using multi-hop technique to realize the communication between two devices which are not in-range is a way to lower the power level.

### 3.3. FlashLinq

FlashLinq works with 5 MHz frequency band in the licensed cellular bandwidth, based on TDD-OFDMA technology which is same as LTE-A system. It can be synchronized by an external clock (e.g. cellular network or GPS) or in-band timing mechanism. Thousands of devices located in proximity can discover one another in a short time and communicate under the FlashLinq system.

The users in FlashLinq can connect, disconnect and communicate with its nearby peers with high data rate persistently. The FlashLinq cannot only enlarge the coverage of cellular network by enabling devices communicate directly, but also support new types of applications to improve the
service of cellular network. It is asserted by Qualcomm that the discovery range can reach up to 950 m in outdoor environment. [4],[9],[16]

Although FlashLinq works in the same bandwidth as cellular network, they design a different physical frame structure for it, compared with LTE-A system. Most of their recent studies are related to the scheduling and protocols of the PHY/MAC layers for it [4],[9],[17],[18]. We can see from their initial objective that FlashLinq does not expect much network assistance from the cellular network. However, as the number of devices increasing rapidly, the performance of FlashLinq can be definitely improved by the network assistance, which is not only synchronization but also many other types.

3.4. **Nokia’s Instant Community**

Nokia’s Instant Community (NIC) is an ad hoc multi-hop platform, which enabling information exchange between local anonymous devices. It is one of the latest energy efficient service and device discovery radio designed by Nokia, and it can work in a high device density [7]. The NIC is based on the Wi-Fi technique, but the connection to a Wi-Fi network is not required. One typical scenario for the application is that people at a football match or a concert share their experience, which can be comments or photos, to nearby anonymity.

Since NIC can support multi-hop communication between devices, all the devices act as relay nodes to pass information for others. In this sense, the network structure of NIC is similar as wireless sensor network, in which a new device can communicate with anyone in an existed ad hoc network after it joins the network.

The main difference between NIC and WSN is that the NIC can benefit from the network assistance once it is available. When a large file needs to be sent by a device in NIC, it can switch to the Wi-Fi network automatically if there is one. [8]

Nokia’s instant community has a very low duty cycle. The beacon opportunity is predefined and all the beacon signals are concentrated in the beacon opportunities. Thus the frequency of transmission times is determined by the interval between the beacon opportunities, which is similar as the transmission probability mentioned in this thesis work. NIC introduces five different working states for devices to reduce unnecessary energy consumption. The devices in advertise state want to be discovered as fast as possible, so they use every possible beacon opportunity to transmit. On contrary, the devices in the keep alive state only transmit at every maximum interval. Therefore, the energy consumption for transmitting and listening largely depends on the interval between beacon opportunities. [7]
4. System Model for Network Assisted D2D Discovery

The system model for D2D discovery and communication has not been defined so far in 3GPP. In order to investigate the influence and relationship among various factors and find out the most effective way of working, a system model with many new concepts is set up in this chapter. Then, the network assistance levels and the related simulation scenarios are defined. The problems which are expected to be solved are presented at the end of this chapter as well.

4.1. Master and Slave

In D2D communication, the types of devices can be various, e.g. mobile phones, laptops, wireless sensors, terminals in restaurants and shops etc. From the perspective of objective, devices can be categorized to two types. One type of devices announce its presence and willingness to communicate, which are called Master devices, while the other type of devices search for masters, which are called Slave devices. (The terminology of masters and slaves here is decoupled from the notion of servers and clients.) In reality, the masters and slaves can be physically separated (e.g. a laptop requires printing service from a neighbor printer) or merged into one node (e.g. a mobile phone in social network intends to not only discover others but also to be discovered by others).

We use the Monte Carlo Methods in our simulation, so in each iteration, we generate the location of devices with 2-dimensional uniform distribution (e.g. in the center cell of the Figure 4.1). To be simple, we consider the single cell case, which lead to dissimilar coverage (the quantity of slaves which can potentially discover a given master) of masters in different positions. The reason for this is the number of slaves which can discover the master near the edge of the cell is much less than that of the other masters, if the slaves out of the center cell are not taken into account. To deal with this, we consider the wrap around of the center cell, as shown in Figure 4.1, the six cells around the center cell are all the duplications of it, and the relative locations of the devices in the duplicated cells are same as that in the center cell. Therefore, the system becomes a multi-cell one, but we only study the center cell with the influence of wrap around cells.

We define the distance between a master and a slave in the center cell to be the real distance (without wrap around) for them, while the virtual distance (with wrap around) between them are defined as the minimal distance between the master in the center cell and all the duplicated slaves in both the center and wrap around cells. In this sense, a master can still be discovered by a slave who has a small virtual distance and large actual distance from it and the number of potential slaves that can discover each master is homogeneous. For example in Figure.4.1, the slaves in the circle but out of the center cell which are covered by the master in the center of the circle can be mapped into the same part (top-left corner) of the center cell. By doing so, the number of slaves covered by the masters near the edge of the center cell can be compensated. We make this assumption in order to build a relationship between the number of potential slaves that can discover a given master and the total number of slaves in the cell, for later use. Unless indicated
particularly, the concept of distance we used in this work always indicates the virtual distance with wrap around.

Additionally, we define one master and one slave to be potential pair (e.g. Ten masters and ten slaves compose one hundred potential pairs.), and after a master has been discovered by a slave, we call them discovered pair.

![Figure 4.1](image-url)

**Figure 4.1** Locations of the devices follow 2-D uniform distribution in the center cell while the six cells around it are all duplications for wrap around.

### 4.2. Beacon Signal and Paging Signal

In a-priori D2D discovery, the masters broadcast Beacon signals when they want to be discovered by others. If a slave can capture this beacon signal, it sends back a Paging signal to the master to inform discovery. The information such as device ID and service ID could be included in these signals as well. If they are included, a master can distinguish paging signals from different slaves, and then it is not difficult for the master to know the number of slaves who have discovered it. Whereas, in some applications, the masters want to be discovered by as many slaves as possible. If there is no knowledge about the quantity of potential neighbors around a master, it never knows how much proportion of slaves have discovered it. Fortunately, the
cellular network can assist with informing the number of its potential neighbors, which can be used by the master to compare with the number of slaves who have discovered it. Then a master can stop transmitting beacon signals and start D2D communication after it has been discovered by most candidates, which are discussed in Chapter 4.10.

We take the paging signals into account in this work, but do not implement them in the simulation, just assume the paging signals are always reliable. We use the received SINR of the signals to evaluate whether a master is discovered by a slave, which is discussed in Chapter 4.6.

4.3. Peer Discovery Resource (PDR)

Figure 4.2 The PDR frame structures for LTE-A (working assumption) and FlashLinq are similar. We assume 12 subcarriers and 14 OFDM symbols to establish one PDR in LTE-A, while FlashLinq use 16 subcarriers and 8 OFDM symbols. There are 2 PDR frames with 100 PDRs (only 1.8MHz used) in each frame in one second interval of LTE-A system while there are around 700 PDRs (5MHz used) in one second interval in FlashLinq.

Compared with traditional peer discovery, one of the main differences for the network assisted D2D discovery is using licensed bandwidth. Peer discovery resource (PDR) is the specific time and frequency (code etc) unit, which can be well planned for device discovery within certain
frequency bandwidth. The structure of PDR is designed and investigated here, but the structure of the beacon signal is out of the scope of this work. Qualcomm presents a good scheme to define PDR structure in FlashLinq system, but it is separated from the LTE-A frame structure. Nevertheless, the PDRs defined in our system model are based on the LTE-A frame structure, which is comparable with FlashLinq.

In FlashLinq system, it is assumed that one PDR is composed of 16 subcarriers with 8 OFDM symbols per each subcarrier, which is shown in Figure 4.2, and 16 milliseconds out of 1 second (one frame) in FlashLinq system are used as PDR, so the duty cycle is 1.6%. Totally, in the 5MHz working bandwidth of FlashLinq, there are 700 PDRs can be used in one frame [18].

Since the structure of PDR has not been defined in 3GPP, we just make a working assumption based on the cellular uplink (UL) frame structure of LTE-A system [19] that 12 subcarriers with 14 OFDM symbols per each subcarrier constitute one PDR, which is equal to two physical resource blocks (PRB) in LTE-A frame structure. Furthermore, we use 2 out of 100 frames (There are 100 frames in 1 second in LTE-A frame structure.) as PDR frame, so the duty cycle is at most 2%. If we use 1.8 MHz of the 5MHz bandwidth, then 100 PDRs can be obtained in one PDR frame (see Figure 4.2). The quantity of PDRs in one frame is scalable and depends on the bandwidth it uses.

The PDRs are only used for transmitting beacon signals rather than paging signals. When a master wants to transmit, it randomly selects one of the PDRs (single PDR) to broadcast a beacon signal. However, whether it is better to use multiple PDRs is analyzed in Chapter 6.1.10.

### 4.4. Propagation Model

The propagation model for D2D has not been standardized in 3GPP. Since the influence of different propagation models on D2D communication is mainly the coverage of masters, which does not affect much on the insight of the system mechanism, we could select the closest propagation model to the D2D wireless environment. The propagation link between devices is not exactly the same as the one between eNB and device. The height of the device antenna is much lower than that of eNB, and the transmission power for devices is also very low compared with eNB, which leads to the limit of coverage for devices. Refer to [20], [21], we use the propagation model expressed as:

\[
G_{PL}^{LOS} = 16.9 \log_{10}(d) + 40.9 + 26 \log_{10}\left(\frac{f_c}{5}\right) \quad (1)
\]

\[
G_{PL}^{NLOS} = 40 \log_{10}(d) + 30 \log_{10}(f_c) + 19 \quad (2)
\]

where \(d\) indicates the distance between devices in meter and \(f_c\) represents the working frequency in MHz. \(G_{PL}^{LOS}\) and \(G_{PL}^{NLOS}\) denote the pathloss gain related to the line-of-sight (LOS) and non-line-of-sight (NLOS) cases separately.

Considering the LOS probability \(a\), we can write the propagation formula in a more general way as:

\[
G_{PL} = a \cdot G_{PL}^{LOS} + (1 - a) \cdot G_{PL}^{NLOS} \quad (3)
\]
where the LOS probability $a$ can be calculated as follows:

$$a = \begin{cases} 
1 & d \leq 4 \\
\exp\left[-\frac{(d - 4)}{3}\right] & 4 < d < 60 \\
0 & d \geq 60 
\end{cases}$$

(4)

In network assisted D2D discovery and communication system, we use 2GHz working frequency which is designed for LTE-A system in cellular network.

Since the process of D2D discovery is very quick, in such a short time we could suppose the lognormal shadow fading does not change much for a given link. For the reason that we are interested in the average performance, the effect of the fast fading is not considered in this model.

### 4.5. Design Objectives and Transmission Power

The type of the devices can be various in the D2D communication. Some of the devices are disposable with small batteries (e.g. button battery), so the energy consumption for these devices should be strictly constrained. Another type of devices has a chargeable battery, so they regard shorter discovery time to be more critical than the energy consumption (e.g. mobile phone and laptop, there is a table about the energy consumption for mobile phone compared with their battery capacity in Appendix.A). From the perspective of energy consumption, we define two design objectives. One is called time priority discovery while the other is energy limited discovery, both of which are investigated within this work.

Obviously, the coverage for a device is very sensitive to the transmission power it uses. The maximal transmission power for the mobile phone in LTE-A cellular network is 24 dBm (ca.251 mW). According to different design objectives, the strategies of transmission power setting are also diverse. In Time Priority Scenarios, we do not need to care too much about the energy consumption. In order to be discovered by as many D2D communication candidates as possible, devices could use the maximal transmission power for each time. On the contrary, in the energy limited scenarios, using higher transmission power also means transmitting for fewer times because of the limited energy budget. Hence, how to deal with this trade-off and find out the best scheme of power setting for these scenarios are discussed in Chapter 6.3.

### 4.6. SINR Based Discovery

The quality of received SINR is used for evaluating whether a master is discovered by a slave. With fast development of the decoding techniques, lower and lower SINR (even below 0 dB) can be decoded at present, which contributes to increasing the coverage of the beacon signals.

Since the masters randomly select PDR to transmit beacon signals, it is possible that two masters use exactly the same time slot and same subcarriers when they transmit. In this circumstance, the signals from different masters cause interference mutually. However, it does not necessarily mean none of the discovery is successful in a collision. Since we use the SINR threshold as the criteria to judge discovery, even in a collision, as long as some (or probably all) of the received
SINRs at a slave from different masters exceed the threshold, we could still consider one or more masters to be discovered at the same time by the slave.

### 4.7. Transmission Probability and Slave Active Probability

*Transmission Probability* ($p_n$) is the probability for a master to broadcast a beacon signal in one PDR frame, which affects much on the performance of discovery. Normally, it can be determined by the preference of the users. In other words, a user can decide when to transmit and when to mute. However, when the number of PDR is insufficient compared with the number of active masters in the cell, the disordered transmission probabilities for different users make the discovery efficiency very low. When the transmission probability is too high, there can be more collisions which cause more interference among different links, thereby prolonging the whole discovery procedure. Inversely, if transmission probability is too small, the usage of PDR can be very low, and the infrequent transmission may also make the discovery time very long. From this perspective, a scientific method for transmission probability setting is necessary, which is conditional largely on the load of the system (related to number of masters willing to be discovered and the number of available PDRs). The methods for transmission probability setting are discussed in Chapter 5.3.

Similar as transmission probability, to save energy consumption, slaves do not need to switch on the receiver in all the PDR frames. The *Slave Active Probability* is the probability for a slave to listen to beacon signals in a PDR frame, which is similar as discontinuous reception (DRX) in cellular network. Low slave active probability can definitely reduce the energy consumption for slaves, but it also causes missing of beacon signals, which may potentially prolong the discovery time. Therefore, there is a trade off related to the slave active probability, and we present a solution approach to this trade-off in Chapter 6.1.9.

### 4.8. Energy Consumption

The energy consumption is a critical factor in our study. We calculate it based on the using of PDRs, which is shown in Figure 4.3. One small block indicates one PDR in PDR frame, where one PDR is equal to 2 PRB in LTE-A system and lasts for 1 ms. The power of transmitter and receiver is listed in Table 3.

At the master side, masters flip a coin with their transmission probabilities in each PDR frame. When one master wants to transmit in one frame, it randomly select one of the PDRs (red blocks in Figure 4.3 (a)) from all of the available PDRs (orange blocks in Figure 4.3). The transmission only lasts for 1 ms interval.

On the other side, the slaves do not know which PDRs are used by the masters, so in order to capture as many beacon signals as possible, they need to listen to all of the available PDRs (green blocks in Figure 4.3 (b) and (c)) in PDR frame. Therefore, the opening time in one frame for the slaves is $L$ ms ($L$ is the number of PDRs in single tone frequency in PDR frame), which is higher than that of masters (1 ms).
The energy consumption for masters and slaves are asymmetric. One small block indicates one PDR (2 PRB in LTE-A which lasts for 1ms). (a) The masters select one PDR (red block) from the available PDRs (orange blocks) to transmit a beacon signal. (b) The slaves listen to all of the available PDRs (green blocks) in all of the PDR frames. (c) If the slave active probability is not full (100%), the slaves only listen to some of the PDR frames (green ones).

If the slave active probability is not 100%, then the slaves only listen to around one out of $N_{\text{open}}$ PDR frames (green blocks in Figure 4.3 (c)), where $N_{\text{open}}$ is the reciprocal of slave active probability. In this case, the energy consumption for the slaves can be reduced, but the beacon signals transmitting in the orange blocks of Figure 4.3 (c) are missed by them.

### 4.9. Probability of Collision and Probability of Collision-avoiding-transmission

A collision occurs when more than one master uses the same PDR to transmit their beacon signals. In a collision, the beacon signals from different masters cause interference to each other, so the avoidance of collision can improve the quality of SINR significantly. In the case that the distances from several masters to a given slave are quite different, the interference caused by collision is too small to affect the performance. Moreover, it can even increase the usage of PDRs. The reuse of PDR with positioning information is not investigated in this work.

We assume the transmission probability for all the masters are same. Before we introduce the definition of the probability of collision, we define two events first, $A_i$ expresses master $i$ transmits, and $B_i$ means there is a collision with master $i$. Then we have $p(A_i) = p(A_j)$ for $\forall i,j$. $N_{\text{PDR}}$ and $N_{\text{master}}$ indicate the number of PDR and the number of masters separately, so the probability of collision for master $i$ can be expressed as:
\[ p_{\text{collision}}(i) = p(B_i|A_i) = 1 - \prod_{j \neq i} \left(1 - \frac{p(A_j)}{N_{PDR}}\right) = 1 - \left(1 - \frac{p(A_i)}{N_{PDR}}\right)^{(N_{\text{master}} - 1)} \quad \forall i. \]  

(5)

In this formula, \( \frac{p(A_j)}{N_{PDR}} \) presents the probability for master \( j \) select the same PDR as master \( i \), and \( \prod_{j \neq i} \left(1 - \frac{p(A_j)}{N_{PDR}}\right) \) denotes the probability for no other masters select the same PDR as master \( i \). In this sense, the probability of collision for master \( i \) can be understood as at least one of the other masters select the same PDR as master \( i \) to transmit their beacon signals.

Another important parameter is called the probability of collision-avoiding-transmission for master \( i \) (\( p_{\text{cat}(i)} \)), which expresses the probability for a master to transmit without collision. In this sense, it also implies the probability for a given slave in the coverage of the transmitting master to obtain relatively high quality of SINR from it. The probability of collision-avoiding-transmission is transformed from [5] defined as:

\[ p_{\text{cat}}(i) = p(A_i) \left(1 - p_{\text{collision}}(i)\right) = p(A_i) \left(1 - \frac{p(A_i)}{N_{PDR}}\right)^{(N_{\text{master}} - 1)} \quad \forall i. \]  

(6)

The \( p_{\text{cat}}(i) \) in Formula (6) is for single master in the system. If the transmission probabilities for the masters are different, then the probabilities of collision-avoiding-transmission are different for the masters as well. Therefore, the average \( p_{\text{cat}} \) over all the masters is more meaningful in evaluating the efficiency of the entire system. In this work, the probabilities of collision-avoiding-transmission are same for all the masters, since we assume the transmission probabilities for them are same. Thus the average probability of collision-avoiding-transmission (\( \bar{p}_{\text{cat}} \)) for all the masters can be written as:

\[ \bar{p}_{\text{cat}} = \frac{1}{N_{\text{master}}} \sum_{i} p_{\text{cat}}(i) = p(A_i) \left(1 - \frac{p(A_i)}{N_{PDR}}\right)^{(N_{\text{master}} - 1)} \quad \forall i. \]  

(7)

According to Formula (7), if the number of PDRs and number of masters are fixed, there must be an option for the transmission probability which can maximize \( \bar{p}_{\text{cat}} \), so we can use this formula to set the transmission probability. But how it performs and whether it is the optimal method still need to be analyzed in Chapter 6.2.2.

It is noteworthy that we do not simply use the method of minimizing the collision probability, because the collision probability becomes zero when the transmission probability is zero. Therefore, both the probability of transmission and probability of collision should be taken into account in determining \( \bar{p}_{\text{cat}} \). The way how to set the transmission probability with this formula is discussed in detail in Chapter 5.3.

### 4.10. Stopping Criteria

It is possible that some of the masters are discovered by enough communication candidates very quickly, even if these discovered masters still send beacon signals, the number of slaves which
have discovered them does not increase much. However, at the same time, they consume more energy and make more interference to other masters. To save energy consumption of masters and reduce the probability of collision, the stopping criteria for masters are introduced.

If a master meets the requirement of stopping criteria, it is muted for the remaining time, which makes the discovery process more efficient. There can be two conditions to mute masters.

- Condition 1: the given master is discovered by at least a certain amount (e.g. \( T=50\% \)) of slaves.
- Condition 2: The number of slaves discover the given master does not change during a certain number of subsequent PDR frames (e.g. \( S=3 \)).

The threshold in Condition 1 can be also set to an absolute number of slaves (e.g. \( T=50 \) slaves), which depends on the requirement of application. These two conditions can be used in two ways.

If they use only the first condition, which is called *Single Stopping Criteria (SSC)*, then all the muted masters can be discovered by at least \( T \) of slaves, so the discovery rate is guaranteed of \( T \). However, if the threshold of \( T \) is set too high, some of the masters cannot reach that amount of slaves due to the noise limitation, and then the masters cannot stop.

They can use either Condition 1 or Condition 2 as stopping criteria at the same time, which we call *Alternative Stopping Criteria (ASC)*. With ASC, some masters are muted by Condition 2, and then the discovery rate is not always guaranteed. To a great extend, it depends on the threshold \( S \). When \( S \) is small, the performance might be very poor, but when it is large, the performance is improved much at the cost of more time and energy consumption.

The information of total number of slaves in the cell is required when stopping criteria are used, and the paging mechanism as well. The performance for these two types of stopping criteria is compared in Chapter 6.1.3.

### 4.11. Degree of Network Assistance

In this section, we discuss how the network can assist in D2D discovery and how devices act according to different degree of assistance from cellular network.

The network can assist in many ways, which are mainly synchronization, informing the number of active masters and slaves, PDR allocation, positioning and so forth. Most of them provided by the network are used by the devices for setting the transmission probability to a proper value, targeting at reducing the discovery time and energy consumption with guaranteed discovery rate. Therefore, the setting of transmission probability is one of the crucial problems for D2D discovery.

With the positioning information, the network can help devices far away from each other to reuse the same PDR, making the usage of PDR more effective. Additionally, with the positioning information, the network can assist with setting the transmission power if the propagation channel can be evaluated. However, the propagation channel is affected much by the shadowing limitation.
and not easy to be predicted accurately with only the positioning information. Thus how to use the positioning information still needs to be investigated in the future.

As far as we know, we are the first to distinguish the degree of network assistance into specific five levels. With higher level, the D2D discovery can benefit more from the network assistance, but at the same time, more signaling and overhead are required. Therefore, finding the level with highest cost-effectiveness is very meaningful for the system designing. We just study the performance with different network assistance levels in this work, and the expense on the signaling can be studied in the future.

Table. 1. Items for different levels of network assistance

<table>
<thead>
<tr>
<th>Network Assistance Level</th>
<th>Synchronization</th>
<th>Broadcast the Number of Active Masters</th>
<th>Broadcast the Number of Active Slaves</th>
<th>Inform Available PDR</th>
<th>Registration Master</th>
<th>Slave</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAL0</td>
<td>YES</td>
<td>—</td>
<td>—</td>
<td>Broadcast</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NAL1</td>
<td>YES</td>
<td>In the Beginning</td>
<td>—</td>
<td>Broadcast</td>
<td>YES</td>
<td>—</td>
</tr>
<tr>
<td>NAL2</td>
<td>YES</td>
<td>In the Beginning</td>
<td>In the Beginning</td>
<td>Broadcast</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>NAL3</td>
<td>YES</td>
<td>Continuous</td>
<td>In the Beginning</td>
<td>Broadcast</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>NAL4</td>
<td>YES</td>
<td>—</td>
<td>—</td>
<td>Unicast</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table. 2 shows the detail of network assistance and whether the registration of masters and slaves are needed according to different levels. With different network assistance levels, we can adopt different strategies.

- **Level 0**: Without the information of the number of masters, there is no good way to find the right transmission probability for masters. To our knowledge, the simplest way is to set transmission probability for each master separately and differently. Another way is trying to find out whether there is an option which is tolerable for all the case.

- **Level 1**: If the number of masters is available in the beginning of the discovery process, with the method which is proposed in Chapter 5.3, masters can use a fixed transmission probability. However, without the number of slaves and paging signal, we cannot introduce stopping criteria at this level.

- **Level 2**: At this level, the information of the number of slaves is available, so the stopping criteria can be used. Nevertheless, the number of active masters is only available in the beginning of the discovery process, without the information about the progress of discovery (the proportion of the active masters which have already been discovered by enough slaves), we can only use fixed transmission probability.

- **Level 3**: If the number of active masters can be available continuously, then the transmission probability could be calculated before each frame with updated information. With stopping criteria, adaptive transmission probability can be used at this level.

- **Level 4**: The network unicasts the PDR to each master. At this level, the stopping criteria and paging signals are not necessary any more. Under the controlling of network, the discovery process is well organized. There is no collision and all the masters only transmit for once,
which makes D2D discovery the most efficient, despite that the cost for the signals are extremely high.

4.12. Simulation Scenarios

From the perspective of design objective, the simulation scenarios can be divided into two types, which are Time Priority Scenario and Energy Limited Scenario. In the Time Priority Scenario, we can even divide them into two subtypes according to whether masters and slaves are physically separate (Scenario AX) or merged into one type of node (Scenario BX). And the number follow the type of scenarios indicates the level of network assistance.

<table>
<thead>
<tr>
<th>Network Assistance Levels</th>
<th>NAL0</th>
<th>NAL1</th>
<th>NAL2</th>
<th>NAL3</th>
<th>NAL4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design objectives and node types</td>
<td>Setting $p_{tr}$ separately or setting empirical $p_{pr}$ for all.</td>
<td>Fixed $p_{tr}$</td>
<td>Fixed $p_{tr}$ with stopping criteria</td>
<td>Adaptive $p_{tr}$ with stopping criteria</td>
<td>Network unicast PDR to each master</td>
</tr>
<tr>
<td>Time Priority AX (separate nodes)</td>
<td>A0</td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
</tr>
<tr>
<td>Time Priority BX (merged nodes)</td>
<td>B0</td>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
</tr>
<tr>
<td>Energy Limited CX</td>
<td>C1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>C2</td>
</tr>
</tbody>
</table>

There is only one main difference between scenario AX and BX. In scenario BX, masters and slaves are merged into one type of nodes, so the transmitter and the receiver of one device share an antenna. Due to the \textit{receiver desensing} (When the transmitter and the receiver share an antenna through the duplexer, if the transmitting power is not suppressed properly in the receiving band, the receiver sensitivity will be largely depraved.) problem, a device cannot hear the beacon signals from other devices in the same time slot when it transmits beacon signal. In other words, some devices may miss the opportunity of discovering other devices when they transmit themselves.

In scenario CX, we emphasize the method of transmission power setting. The network assistance levels in the Energy Limited scenarios are not same as the Time Priority Scenarios, and we only analyze the lowest and highest levels.

The performance for different strategies within each scenario is compared, and the performance for different scenarios is compared as well, in Chapter 6.2 and 6.3.

4.13. Simulation Parameter Setting

The results of this work are based on the \textit{Rune} simulator and \textit{Monte Carlo} Methods. The parameters used in this work are all listed in the following table. The parameters in left column
are fixed and used for setting up the wireless model while the parameters in the right column are the ones we want to investigate in this work.

Table 3. Simulation parameter setting

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Summary</th>
<th>Parameters</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>System bandwidth</td>
<td>5MHz</td>
<td>Node types</td>
<td>Separate, Merged</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2GHz</td>
<td>Energy consumption</td>
<td>Limited, Unlimited</td>
</tr>
<tr>
<td>Max transmission power</td>
<td>24 dBm</td>
<td>Network assistance levels</td>
<td>5 levels</td>
</tr>
<tr>
<td>Power of receiver</td>
<td>20.4 dBm</td>
<td>Transmission probability</td>
<td>Fixed, Adaptive</td>
</tr>
<tr>
<td>Thermal noise N</td>
<td>-107 dBm</td>
<td>Number of PDRs</td>
<td>16, 36, 64, 100…</td>
</tr>
<tr>
<td>Pathloss factor</td>
<td>4 (NLOS)</td>
<td>Cell Radius</td>
<td>500m, 1000m…</td>
</tr>
<tr>
<td>Lognormal shadow fading</td>
<td>6 dB (NLOS)</td>
<td>Slave active probability</td>
<td>25%, 50%, 100%…</td>
</tr>
<tr>
<td></td>
<td>3 dB (LOS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of TX antenna</td>
<td>1</td>
<td>PDR selection</td>
<td>Random, Unicast, Multiple PDR</td>
</tr>
<tr>
<td>Number of RX antenna</td>
<td>1</td>
<td>Stopping criteria</td>
<td>SSC T=50%, ASC T=75% S=3</td>
</tr>
<tr>
<td>SINR target</td>
<td>1 dB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of masters in the cell</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of slaves in the cell</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.14. Problem Formulation and Performance of Interest

There are many factors that can affect the process of D2D discovery, and many questions related to D2D discovery are interested by both researchers and system designers. We aim at finding out the answers for the following questions in this work.

- In which way can the network assist in discovery phase for D2D communication?
- What is the performance for D2D discovery with different degrees of network assistance? How can the performance be improved from a lower level of network assistance to a higher level?
- What type of mechanism can be introduced in the D2D discovery to increase the efficiency?
- How to design the transmission probability according to different network assistance levels?
- How can the quantity of available PDRs in PDR frame affect the discovery time?
- Which scheme is the best in selecting PDR for a transmitting master?

In order to make the performance for different scenarios easy to perceive and comparable, we introduce some metrics to measure the performance.
**Discovered masters** are the masters which have been discovered by at least a certain amount (threshold ‘$T’’) of the slaves. The option for threshold ‘$T$’ depends on the quality of SNR for all the potential pairs and it should be set a bit lower than the average amount of slaves covered by one master.

**Discovery time** is the time for all the masters to become discovered masters within the area of study. If not all masters can become discovered masters (e.g. ‘$T$’ is too high with respect to the noise limitation of beacon detection), the discovery time with respect to ‘$T$’ tends to infinity, so the setting of ‘$T$’ is very important to the process and results of the discovery.

**Discovery rate** is the ratio of the number of discovered pairs to the total number of potential pairs. It can be used for evaluating the progress of the discovery and constraint of the largest discovery amount.

**Energy consumption** for masters and slaves is calculated separately. The masters consume energy only when they transmit beacon signals, while the receivers of slaves also consume energy when they open and listen to the PDR frames.

**Number of used PDRs** is a very important index for the system usage. Although a larger quantity of PDRs in PDR frame almost always yields better performance in terms of reducing the discovery time, it requires more frequency bandwidth or higher duty cycle.
5. Solution Approach

We draw the problems of this work in Chapter 4.14 after introducing the concepts and model, so in this chapter, we present the approaches to solve these problems. First, we make some assumptions for our study. Then, we investigate how the key parameters influence the mechanism of the D2D communication system.

5.1. Assumptions

The devices works in Wi-Fi Direct and Bluetooth are not synchronized, so the discovery between the devices is an energy consuming process. Thus, in our algorithm, we assume that the network can provide at least the synchronization to the devices, and the resources used for peer discovery are fixed in the frame structure.

To make it simple, we only simulate the beacon signals in the model, and assume all the paging signals are always reliable without missing and colliding. In consequence, none of the energy consumption for sending and detecting for the paging signals is calculated in this model. Additionally, it is assumed that the slaves can decode different beacon signals in different frequency simultaneously.

We study the single cell case but with wrap around in this model, which is not exactly the same as the multi-cells case. In the former case, we duplicate the masters and slaves to the wrap around cells, which can be found in Figure 4.1, so there are one-to-one correlations between the devices in different cells, but not in the latter one. We define the real distance and virtual distance in Chapter 4.1, so the maximal real distance between a master and a slave can be $2R_{\text{cell}}$ ($R_{\text{cell}}$ is the radius of the cells) while the maximal virtual distance is much smaller than the real one. (The CDF of distances between the masters and slaves can be found in Figure 6.1. of the next chapter.) In order to obtain homogeneous devices in the system (no difference of the coverage between the master near the edge of the cell and the one near the center of the cell) in the single cell case, we use the virtual distance in our work.

Generally, the users have their own preference to start or stop discovery. When the number of PDRs is sufficient compared with the number of users in the area, the transmission probability can be determined by the users directly. However, with increasing of the quantity of the devices, the spectrum for D2D discovery and communication will run out, and the number of PDRs will be quite limited compared with number of devices. In this case, the transmission probability should be organized in a good way to make sure all of the devices can achieve discovery with high efficiency, where the network assistance is demanded.

Since the time for discovery process is not long, we can simply assume the location of users are relatively stable, and the shadow fading for different links are unchanged in one discovery process. We do not consider the fast fading in this work.
5.2. Transmission Probability Setting

In this work we have three methods to set the transmission probability. The first one is \( \text{Max}(\bar{p}_{\text{cat}}) \), in which we find the \( p_{tr} \) to maximize \( \bar{p}_{\text{cat}} \) according to Formula (7), the solution for it is \( p_{tr} = \min \left\{ \frac{N_{\text{PDR}}}{N_{\text{master}}}, 1 \right\} \). It is very simple to achieve with this method, and the \( p_{tr} \) is lower than that of the other methods.

The second one is to select the \( p_{tr} \) which can maximize the average number of discovered pairs in one frame (abbreviated as Max (#discovered pairs) or Max(#dp)). The numbers of masters and slaves are denoted as \( N_{\text{master}} \) and \( N_{\text{slave}} \) respectively. Obviously, the number of discovered pairs in one frame is related to two factors. One is the number of potential pairs which can get discovery if no collision occurs (i.e. \( N_{\text{master}} \cdot p_{tr} \cdot N_{\text{slave}} \)), and the other is the influence of collision on the SINRs of these pairs, which implies some of the potential pairs may fail to get discovery due to the collisions. In addition, the probability of collision is increasing with \( p_{tr} \). Consequently, there is an optimal \( p_{tr} \) which can maximize the average number (over many iterations) of discovered pairs in one frame for the concave function between them. We can use the method of exhaustion to obtain this value, so it is more sophisticated than the first method.

Intuitively, if the total number of potential pairs is fixed in the beginning of the discovery process and the \( p_{tr} \) determined by this method can maximize the average number of discovered pairs in one frame, then the number of frames for the entire discovery procedure should be the minimum. However, whether it is as we expected is verified in Chapter 6.6.2.

In the third method, the \( p_{tr} \) which minimizes the discovery time (with guaranteed discovery rate) is selected. We consider this method as the optimal one, because it matches the design objective of Time Priority Scenarios, however, it is the most complicated one as well.

The discovery time is defined previously as the time for all the masters to be discovered, so it largely depends on the threshold that evaluates whether a master is discovered (e.g. threshold of stopping criteria). For fixed \( p_{tr} \) cases, we can use the method of exhaustion to find the optimal \( p_{tr} \) (which take the minimal discovery time with guaranteed discovery rate, e.g. in Figure.6.5) for different cases. However, for adaptive \( p_{tr} \) cases, the optimal method must be the combination of optimal strategies in each frame. It can be approached by formulating Markovian Decision Process (MDP), which is out of the scope of the current work. Some of the differences among the three methods are compared in Table.4.

<table>
<thead>
<tr>
<th>Method of setting the transmission probability</th>
<th>Complexity of achieving</th>
<th>Fixed ( p_{tr} )</th>
<th>Adaptive ( p_{tr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max (( \bar{p}_{\text{cat}} ))</td>
<td>Easy</td>
<td>Low ( p_{tr} )</td>
<td>Low ( p_{tr} )</td>
</tr>
<tr>
<td>Max (#discovered pairs)</td>
<td>Medium</td>
<td>High ( p_{tr} )</td>
<td>High ( p_{tr} )</td>
</tr>
<tr>
<td>Min (discovery time)</td>
<td>Difficult</td>
<td>Optimal ( p_{tr} )</td>
<td>Optimal ( p_{tr} ) (MDP)</td>
</tr>
</tbody>
</table>
All these three methods require information about the number of available PDRs and the number of active masters in the cell. If it is only available in the beginning of discovery process, they can only use fixed transmission probability, while if the number of active masters is available continuously, they can use adaptive transmission probability to match the variation of the number of active masters in the system.

From the actual perspective, only one calculation is needed to find the $p_{tr}$ each time for the first method, so maybe it is better to use the real-time calculating rather than searching in a large table, which needs initialization of the table and memory to store them. In contrast, the mechanisms for the latter two methods are complex and time-consuming, so it is unrealistic to do it in real-time. They can make a table to store the $p_{tr}$ according to different scenarios, and select the proper one when masters transmit. However, they have to finish the initialization of the tables before the actual discovery phase, and the data can be stored in either the eNB or the device memories. There is still a problem that the values in the table depend strongly on the wireless environment and the locations of the users, so the accuracy is not very high, and the process of designing the tables is complex and costly.

### 5.3. PDR Selection Strategy

To be simple, each master only select one PDR to transmit its beacon signal. However, whether it is better to use multiple PDRs is still a question, the simulation results with respect to this are drawn in Chapter 6.1.8. We also compare two different schemes for the multiple PDR selection to see which one is better and more executive.

![Figure 5.1](image.png)

**Figure 5.1** There are two schemes for multiple PDRs selection (e.g. $n=2$ PDRs). In scheme 1, they first pick $n$ PDR time slots randomly, and then use a random PDR in each PDR time slot, so the $n$ picked PDRs cannot in the same PDR time slots. In scheme 2, all the PDRs are divided into $n$ blocks in time domain, and then randomly pick one in each block.

In the Time Priority Scenarios, the transmission power is always set to the maximum. In order to make it possible, they cannot pick multiple PDRs in the same PDR time slots. Otherwise, the maximal transmission power has to be divided into several portions for different PDRs (frequency) to use. There are two schemes for multiple PDRs selection, and assume $n$ is the number of PDRs that one master uses at one time in the multiple PDRs case. Thus in scheme 1, one master randomly select $n$ PDRs to transmit, but all of them have to be picked from different
PDR time slots, while in scheme 2, we first divide the PDRs into $n$ blocks in time domain, and then the master randomly picks one PDR from each block to transmit beacon signals. The two schemes can be found in Figure.5.1.

Interestingly, the $\tilde{p}_{cat}$ is same for both scheme 1 and scheme 2 in multiple PDRs selection case, which is expressed as follows:

$$\tilde{p}_{cat} = \frac{1}{N_{\text{master}}} \sum_i p_{cat}(i) = p(A_i) \left( 1 - \left( 1 - \frac{n}{L \cdot M} \right)^{N_{\text{master}} - 1} \right)^n \forall i.$$  

(8)

The detailed derivation for this formula can be found in Appendix.B. When $n$ decreases to 1, this formula is cleared to the single PDR case, which is same as Formula (7).

Therefore, there is no difference on the performance between the two schemes. However, scheme 2 is well ordered and clear for comprehension, which is similar as the case of using $1/n$ of the PDRs to transmit $n$ times in single PDR selection. From this perspective, using multiple PDRs in sufficient PDR case can increase the usage of PDR and save the discovery time.

### 5.4. Working with Stopping Criteria

Obviously, the users can decide when to start and stop discovery, but some applications may need large quantity of D2D communication candidates, and this liberal open and close may lead to poor discovery rate. To reach a higher discovery rate, a master may continuously transmit beacon signals, but the efficiency may be very low, as it not only cause more mutual interference but also cost more energy.

For this reason, if a master has the knowledge about the quantity of slaves around it and the quantity of slaves which have already discovered it, stopping criteria can be used for muting this master and the discovery rate is guaranteed. The paging signals from slaves to masters are required when using stopping criteria. Take the advantage of the paging signals, a master knows the number of slaves which have discovered it, if it can distinguish the paging signals from different slaves. After that, if the number of slaves around the master is available from the network assistance, the master can compare the ratio of these two numbers with the threshold of the stopping criteria. If it meets the requirement, the master can stop transmitting beacon signals. Therefore, the stopping criteria are very helpful in the process of D2D discovery, which should be used as much as possible. The performance is sensitive with the setting of the thresholds for stopping criteria conditions, which is studied in Chapter 6.1.3.
6. Numerical Results and Performance Analysis

After discussing in previous chapters, we understand how the D2D discovery works and which factors could influence the performance of the system. In this chapter, we focus on analyzing the graphical and numerical results, from which we can obtain deeper understanding about the principle of the D2D discovery. The results shown in this chapter are based on some basic assumptions and setting up of the system. So we first present the results related to the setting up of the simulation model, and then the performance of different scenarios is analyzed and compared in the subsequent sections.

6.1. Simulation Setting Up

6.1.1. Distance between Masters and Slaves

![Figure 6.1](image)

Figure 6.1 There is significant difference between the CDF of real distance and virtual distance between masters and slaves ($R_{cell}$=500 m). The real distance of a potential pair is the distance between the master and slave in the center cell without considering wrap around of the center cell. The virtual distance of a potential pair (with wrap around) is the minimal distance from the master in the center cell to all the slaves in both the center cell and wrap around cells.
If we only consider the D2D discovery without network assistance, we do not need to think highly of the concept of the cellular network. However, in order to investigate the influence of the network assistance on D2D discovery, we have to put the location information of devices in the region of cellular network. In this sense, the average distances between masters and slaves in the study area (one cell) are greatly determined by the size of the cell. If the radius of the cell is small, the attenuation of the links between masters and slaves is also small, so the probability of discovery between the potential pairs is high, and vise versa.

The definitions of the real distance and virtual distance are given in Chapter 4.1. The cell radius is set to 500 m in the simulation model, intuitively, the largest real distance between a master and a slave can be 1000 m. From Figure 6.1 we can see that the maximal real distance is only 900 m, since it is not very likely to happen that two devices are both at the edge of the cell in exactly the opposite direction. We consider the wrap around of the study cell, in other words, we only study the center cell in the multi-cell system. After mapping the devices to the duplicated cells, there are seven different virtual links between each pair, and we select the minimal distance for them as the virtual distance. Thus the devices which are far away from each other in the center cell (with large real distance) might be considered close to one another (with small virtual distance). Consequently, the virtual distances between potential pairs (up to only 500 m) are much smaller than the real distances (up to 900 m).

In the propagation model, we assume two different formulas for the line-of-sight (LOS) case and non-line-of-sight (NLOS) case separately. We consider the LOS case only if the distance of the pair does not exceed 60 m, and the proportion of this kind of pairs is less than 4%, so the influence of the LOS is very small.

![Figure 6.2](https://via.placeholder.com/150)

**Figure 6.2** The CDF of SNR is over all the potential pairs based on the virtual distances. The potential pairs which SNRs are lower than the SINR target (1 dB) cannot achieve discovery due to the noise limitation.
6.1.2. CDF of SNR

The received SNR of one link is the maximal limit for SINR, which can be reached only in the interference free case. From this point of view, the number of potential pairs that can achieve discovery is determined by the CDF of SNR.

In this simulation, we set the SINR target to 1 dB. From Figure.6.2, we can see that more than 70% potential pairs are able to achieve discovery, while the other less than 30% of potential pairs cannot achieve discovery even when the masters transmit without collision, which is caused by the noise limitation. The threshold option for condition 1 of stopping criteria also depends on the CDF of SNR, which is affected indirectly by the transmission power and cell radius.

6.1.3. Stopping Criteria

Figure.6.3 Comparison of the single stopping criteria (SSC) with the alternative stopping criteria (ASC) in terms of discovery time and discovery rate for both insufficient and sufficient PDR cases.
The principle and function of the stopping criteria are discussed in previous chapters. It contributes much in the process of discovery to reduce the energy consumption and collisions. It can be used in network assistance level 2 and 3. The stopping criteria can work with high efficiency, if the threshold of stopping criteria is set properly.

In SSC, we use $T=50\%$ as the threshold, which is lower than the average proportion of pairs whose SNR exceeds 1 dB (around 70\%). The setting of threshold $T$ cannot be too high, in that some of the masters are not able to cover that quantity of slaves. Also, it cannot be too low, for the reason that part of the masters might be muted too early when they are only discovered by a small quantity of slaves but able to be discovered by much more. In ASC, to reach relative better performance, the threshold can be set to $T=75\%$, which is around the average proportion of pairs whose SNR exceeds 1 dB. On the other hand, we set the threshold $S=3$ for condition 2. And better discovery rate can be obtained, if $S$ is set higher, although more discovery time and energy consumption are cost.

Both the number of masters and number of slaves are set to 100 separately in the simulation except when indicated otherwise. In Figure 6.3, the above two subplots are related to the case which number of PDRs is 16, while the bottom two subplots are for 100 PDRs case. As we see in the top right subplot, when the quantity of PDR is insufficient and the transmission probability is large, we say the system is in a high load. In this case, the discovery rate for ASC is very poor, for parts of the masters are muted by the second condition of ASC. In this high collision case, although the number of slaves that discover a given master does not change during 3 subsequent PDR frames, it is possible that they collide in all these three times. In contrast, the discovery rate for SSC in this case in acceptable. When the transmission probability is low, the discovery rates for both ASC and SSC are acceptable, but the discovery time for ASC is always larger than SSC. As a result of this, SSC performs better in the insufficient PDR case.

**Figure 6.4** Discovery time and discovery rate as a function of a fixed transmission probability for single stopping criteria (SSC) and alternative stopping criteria (ASC) with different threshold setting in insufficient PDR case.
When the quantity of PDRs is increased to 100, the collision probability is decreased to a very low level. The discovery rate for both ASC and SSC are good, but the discovery time for ASC is still larger than SSC. Therefore, SSC is still better than ASC in the sufficient PDR case.

The above comparison about ASC is based on the threshold $S=3$, the difference of the performance with other option of threshold $S$ is compared in Figure.6.4 with 16 PDRs. We can see that the higher discovery rate can be reached with a higher $S$, which also indicates larger discovery time. Even though, the discovery rate for ASC $S=5$ is still not as good as that for SSC on average, but the discovery time is higher than SSC in most of the cases. In order to reach the same discovery rate as SSC, we need even larger $S$ for ASC, which costs larger discovery time and more energy consumption. Therefore, in the following, we use SSC as stopping criteria in the simulations.

### 6.1.4. Optimal Fixed Transmission Probability

Using fixed transmission probability is very simple to achieve in reality, when the information about the number of active masters in the cell is only available in the beginning of discovery process. Moreover, even if the masters do not have any information about the number of active masters in the cell, the masters can still use a fixed transmission probability. Thus the fixed transmission probability can be used with NAL0-2. In most of the cases, there is an optimal option for the transmission probability ($p_t$), in terms of minimal discovery time with guaranteed discovery rate. With stopping criteria, the number of active masters decreases during the whole discovery process. Thus the optimal fixed $p_t$ cannot be always the most effective one from the beginning to the end, it is the global optimum. From the example shown in Figure.6.5, we can
see that there is an optimal option for both the sufficient (#100) PDR case and insufficient (#16) PDR case. To this specific parameter setting, the optimal $p_{tr}$ appears around 50% in the insufficient PDR case, while that is 100% (i.e. transmitting in all PDR frames) when there are sufficient PDRs to use.

### 6.1.5. Methods for Setting Adaptive Transmission Probability

Using adaptive transmission probability can make the discovery process more effective from the beginning to the end, by means of fitting the changing of the population in the cell and adjustment of available PDRs. Besides the information about the number of active masters is required continuously, the calculating for adaptive transmission probability is tedious as well. Refer to Chapter 5.2, we have mentioned three methods for the $p_{tr}$ setting. The optimal one which minimizes the discovery time with guaranteed discovery rate is extremely complex to achieve, which can be approached by formulating MDP and out of the scope of this work. We focus on the other two which are more executable.

![Transmission probabilities according to the methods of Max(#dp) and Max($p_{cat}$) for different number of active masters are compared, when the number of PDR is 16. The $p_{tr}$ obtained from Max($p_{cat}$) is much lower than the other one. It is redundant to find the $p_{tr}$ for different number of active masters for Max(#dp), so it is better to find some $p_{tr}$ first and then use poly fitting method to complete the curve.](image.png)

**Figure 6.6** Transmission probabilities according to the methods of Max(#dp) and Max($p_{cat}$) for different number of active masters are compared, when the number of PDR is 16. The $p_{tr}$ obtained from Max($p_{cat}$) is much lower than the other one. It is redundant to find the $p_{tr}$ for different number of active masters for Max(#dp), so it is better to find some $p_{tr}$ first and then use poly fitting method to complete the curve.

We take an example for the case when the number of available PDR is 16, so the $p_{tr}$ according to the methods of Max(#dp) and Max($p_{cat}$) for different number of active masters can be found in Figure 6.6. According to the decreasing quantity of active masters in the cell, we can easily find
the increment of the transmission probabilities of both methods. The transmission probability for method $Max(p_{cat})$ is much lower than the other one, and the performance of these two methods is compared in Chapter 6.2.2.

As mentioned in Chapter 5.2, from the perspective of practical applicability, the method of $Max(p_{cat})$ is more suitable to calculate the $p_{tr}$ in real-time, with the updated information on the number of active masters and the number of available PDRs. However, for the method of $Max(#dp)$, it is unrealistic to calculate the $p_{tr}$ each time, and the best way for it is to make a table for different cases and search for the proper one when the masters transmit. This table can be stored at either the side of eNB or the device side. We have to use exhaustive testing method to find the optimal $p_{tr}$ for each case, so it is redundant to find the $p_{tr}$ for all the possible cases by $Max(#dp)$ method. To be simple, we can find the $p_{tr}$ for some of the typical cases and then use poly fitting method to complete the table.

### 6.1.6. Effect of PDR Amount

The total quantity of PDRs is determined by the available frequency bandwidth for D2D discovery and the duty cycle of the PDR frames. Although more PDRs always imply better performance, in terms of less discovery time with guaranteed discovery rate, the wireless resource is very limited in both time domain and frequency domain. Thus both the efficiency of discovery process and resource consumption should be taken into account at the same time.

![Figure 6.7](image-url) **Figure 6.7** Discovery time and discovery rate as the function of the number of PDRs, for the case of using fixed transmission probability (20%) with ASC ($T=75\%$, $S=3$) and SSC ($T=50\%$).

Since the method of setting $p_{tr}$, both of fixed and adaptive, is based on the quantity of available PDRs, it is obvious that the discovery time can be reduced with larger number of available PDRs (e.g. Figure.6.21). However, to a specific setting of fixed $p_{tr}$, there is a threshold for the number of PDRs when more than that threshold quantity of PDRs are used, the discovery time can hardly be reduced. For example in Figure.6.7, the $p_{tr}$ is fixed to 20% in the beginning, the discovery...
time is not changed for all the cases when the number of PDR is larger than 60 (the threshold for this case), and the discovery rate is quite stable as well. Therefore, more than that quantity of PDR means a waste of resource, and that is the reason why we mentioned in Chapter 4.8 that not all of the PDRs are necessary to be used in all the cases.

### 6.1.7. Effect of Slaves Active Probability

![Graphs showing the effect of slaves active probability on discovery time, discovery rate, and energy consumption.]

**Figure 6.8** Comparison of the performance, in terms of discovery time, discovery rate and energy consumption, with different slave active probability indicates that the full switching on (100%) for the slaves is the best. The example uses fixed $p_{tr}$ with SSC ($T=50\%$).

The energy consumption for masters is in a high efficiency, since the masters know when to broadcast beacon signals. In contrast, the slaves have no knowledge about when the masters transmit and which PDRs they use. In order not to miss beacon signals, the slaves have to listen to the entire PDR frame and all of the PDR frames. If the transmission probability for masters is not high, most of the waiting time for the slaves is in vain, so the efficiency of the slaves is very low. Hence, the slaves can switch off in some PDR frames to save energy consumption if the influence on beacon signal missing is not severe.
However, the simulation results might depress us that lower slave active probability does not always give rise to lower energy consumption for slaves. For instance in Figure.6.8, we use fixed transmission probability with SSC. It can be seen in the bottom right subplot that the energy consumption with 25\% slave active probability during the discovery process is even higher than that with 50\% slave active probability, when $p_n$ is in the range of 80\%-100\%. Moreover, lower slave active probability depraves the performance in all the other aspects, in terms of discovery time, discovery rate and energy consumption for masters, which can be easily found in the other three subplots. The reason for this is low slave active probability leads to a large amount of signal missing, so discovery process is prolonged and consumption for masters is increased as well. Consequently, using full (100\%) slave active probability is better than partly switching on, and we use full slave active probability in our simulation model.

### 6.1.8. Using Multiple PDRs

![Comparison between single PDR selection and multiple PDR selection](image)

**Figure.6.9** Comparison between single PDR selection and multiple PDR selection, in terms of discovery time, discovery rate and energy consumption, shows that using single PDR is always better than multiple PDR except when the system load is low. The example uses a fixed $p_n=30\%$ with SSC ($T=50\%$) and number of PDRs is 16.
As discussed in Chapter 5.3, the single PDR selection is of the lowest complexity to achieve in reality, and the energy consumption for it is the lowest as well. On contrary, with multiple PDRs ($n$ PDRs) selection, the opportunity of transmission is increased by $n$ times, but the collision probability is also increased, which may not yield a higher opportunity of discovery. What is more, the multiple PDRs selection leads to more energy consumption for the masters.

The performance with different number of PDRs selection schemes is compared and shown in Figure.6.9. The available number of PDRs is 16, and the transmission probability is set to 30%, with SSC ($7=50\%$). When the system is in a high load (high transmission probability, large number of active masters, insufficient PDRs), using single PDR in always better while in a low load case (PDR is sufficient compared with number of active masters), using multiple PDR outperforms single one. For example, from the up-left subplot, we can see the discovery time of single PDR selection is always the smallest when the number of active master is larger than 70, and when it is smaller than 70, the red curve (2 PDRs selection) become better than the blue one, but there is only slight difference. The case is similar for even more PDRs selection methods. Additionally, in the up-right subplot, it is obvious that the method of single PDR selection can always achieve the best discovery rate. Therefore, to make it simple, we use the single PDR selection in this work.

### 6.1.9. Effect of the Cell Radius

![Figure 6.10](image)

**Figure 6.10** CDF of the distance (both virtual and real) and SNR for all the potential pairs with different cell radius. If the population of the users in the cell does not change, the distances between all the potential pairs are increased with the increasing of cell radius, and the quality of SNR is significantly declined.

The difference between the virtual distance and real distance is whether to consider the wrap around of the center cell, which can be found in Figure.4.1. Since the number of active masters is fixed in our model and devices are located uniformly in the center cell, the distances between all the potential pairs depend strongly on the cell radius. From the left subplot of Figure.6.10, the distances are doubled when the cell radius changes from 500 m to 1000 m. Therefore, with the
same transmission power of the masters, the received SNRs at all the slaves from all the masters become inferior. It can be easily seen from the right subplot of Figure 6.10 that only around 20% pairs are able to achieve discovery (the received SNR is large than the SINR target 1 dB) when the cell radius is 1000 m, which is significantly decreased, compared with the case (around 70%) when cell radius is 500 m.

### 6.2. Time Priority Discovery Scenarios

In the Time Priority Scenarios, we aim at minimizing the discovery time with guaranteed discovery rate, so the ASC cannot be used in these scenarios, and the energy budget is relatively sufficient. In this section, we first investigate the strategies and performance for each scenario, and then make comparison among different scenarios. In AX scenarios, the masters and slaves are considered separately, while in BX scenarios they are merged into one type of node.

#### 6.2.1. Scenario A0 (NAL0): Empirical Fixed $p_{tr}$

In this scenario, the cellular network only provides synchronization to devices. Without the information about the number of active masters in the cell, it is not possible for a single device to find an optimal transmission probability. The simplest way is to set the transmission probability randomly over [5%, 100%] (Theoretically, the interval should be [0, 100%], but a small transmission probability may lead to a long discovery time, so we just set 5% as the minimal value.) for each master, so different masters use different transmission probabilities and these probabilities follow a uniform distribution over [5%, 100%]. The only advantage for this method is its simplicity, but the system is not well ordered and the usage of the resource is not high.

![Figure 6.11](image)

**Figure 6.11** Discovery time and discovery rate as the function of fixed transmission probabilities for different number of active masters. In scenario A0, with increasing of the number of active masters in the cell, the optimal fixed transmission probability become smaller and the difference of discovery time between optimum and non-optimum is more obvious.
Compared with *random transmission probability*, setting an empirical value for all the masters seems to be more reasonable if there is a good option for different cases, which is called *universal transmission probability*. With this objective, we draw Figure.6.11 for this scenario with 16 PDRs, and the number of active masters is from 20 to 300. The masters do not use stopping criteria at this level due to the lack of useful information.

![Figure 6.11](image1)

**Figure.6.12** Performance of Scenario A0, in terms of discovered masters with time as well as discovery rate and energy consumption. The method of using universal $p_{tr}$ outperforms the random one.

It is very clear in Figure.6.11 that the discovery rates are quite stable for all the cases, so we could pay more attention to the discovery time. When the number of active masters is small (e.g. 20 or 50), the optimal transmission probability tends to be higher (around 100% or 50%). What is noticeable is that the difference of discovery time is very small when $p_{tr}$ is larger than 10%. In other words, the discovery time for non-optimal transmission probability is still acceptable compared with optimum. On the other hand, when the number of active masters is large (e.g. 300), using a smaller transmission probability (about 8%) tends to be better, but the difference in discovery time between optimal and non-optimal transmission probability is quite significant this time. Fortunately, the optimal $p_{tr}$ for different number of active masters are quite close (around...
10%) when the number of active masters is large. Therefore, even without any information about the total number of active masters in the cell, using an empirical option (e.g. 10%) for transmission probability is universally profitable for all the number of masters.

Definitely, taking 10% as the universal transmission probability is not always the best option. It is determined by the specific parameter setting and wireless environment of the model. However, the method of finding the universal transmission probability presented above is practical.

Figure 6.12 shows the comparison of performance between the two strategies of setting $p_{tr}$ without information about the number of active masters in the cell, the number of PDR is 16. The performance with the universal $p_{tr}$ (10%) outperforms the random one (random over [5%, 100%]) in all aspects. Although the discovery rate for random $p_{tr}$ is bit higher than the universal one in the beginning, the number of discovered master is still lower. The difference of the performance between these two strategies also depends on the number of active masters in the cell, if the universal $p_{tr}$ can be scientifically designed, it can be always better than random $p_{tr}$.

### 6.2.2. Scenario A1 (NAL1): Fixed $p_{tr}$ without Stopping Criteria

![Performance of Scenario A1, in terms of discovered masters with time as well as discovery rate and energy consumption. The performance of Max($p_{cat}$) method is very close to the optimal one and much better than the Max(#dp) one.](image-url)
In this scenario, the network broadcasts the number of active masters in the beginning of the discovery process. However, without the information about the number of slaves and paging signals, a given master do not know the number of slaves which have discovered it and the stopping criteria cannot be introduced in this scenario. The master devices simply use a fixed $p_{tr}$ since the number of active masters does not change. Because the masters discovered by more than $T$ slaves (fulfill the single stopping criteria) do not have information about such changes.

We still use the three methods of setting $p_{tr}$ discussed in Chapter 5.2. The discovery time is defined as the time for all the masters to be discovered by at least a given amount ($T=50\%$ in this model) of slaves, so in the optimal method, we minimize discovery time with guaranteed discovery rate (e.g. 50% of slaves), which is also the most complex to achieve in these three methods. The $\text{Max}(p_{\text{cat}})$ one is easy to obtain through Formula (7) while the last $\text{Max}(\#dp)$ one is a medium one in complexity but performs the worst. The performance with different fixed transmission probabilities obtained from these three methods is compared in Figure.6.13, and the number of PDRs is 16. The most interesting thing that we can find from the figure is the difference in terms of discovery time and the energy consumption between the optimal one (green curve) and the $\text{Max}(p_{\text{cat}})$ (blue curve) one is slight, and it is almost impossible to distinguish the two curves in the first subplot. However, the complexity for $\text{Max}(p_{\text{cat}})$ method is significantly lower than the optimal one. Therefore, we call the method of $\text{Max}(p_{\text{cat}})$ suboptimal one, which is very close to the optimum and is easy to execute in really. Both of these two methods outperform the $\text{Max}(\#dp)$ one in all aspects.

![Comparison between Max(#dp) method and Max(p_cat) method in terms of the discovered pairs in one frame. In this work, the threshold for distinguishing whether a master has been discovered (by enough candidates) is set to 50%.

Figure.6.14 Comparison between Max(#dp) method and Max(p_cat) method in terms of the discovered pairs in one frame. In this work, the threshold for distinguishing whether a master has been discovered (by enough candidates) is set to 50%.
One question is raised that since the $\text{Max}(#dp)$ method can maximize the number of discovered pairs in one frame, is it the same as maximizing the number of discovered masters (masters that have been discovered by given (e.g. $T=50\%$) amount of slaves) simultaneously? Intuitively, if the number of potential pairs is fixed in the beginning, this method should be the optimal one in terms of minimizing the number of frames for discovery process. What is interesting, the results in Figure.6.13 show totally the opposite, the performance of $\text{Max}(#dp)$ method is not as good as $\text{Max}(p_{\text{cat}})$, and the difference between this and the optimal one is obvious. We try to find the answer to this question from Figure.6.14.

In Figure.6.14, the X-axis expresses the proportion for the quantity of slaves in the cell, while Y-axis denotes the proportion for quantity of masters which are discovered by at most $X$ slaves in one frame. For example, the blue points on the blue curve from left to right stands for 83% of masters are not discovered by any slaves, 94% of the masters are discovered by at most 50% of the slaves and 100% of masters are discovered by at most 80% of the slaves (due to the noise limit). Additionally, we can also explain the meaning of the blue point on the dashed line in the opposite way that 6% of the masters are discovered by at least 50% of the slaves, which indicates the discovered masters if the threshold is set to 50%. Similar for the red curve, there are only 50% of masters are discovered by zero slaves and the amount of masters that are discovered by at most 50% of slaves is 98%, and the red point on the dashed line can be explained as 2% of the masters are discovered by at least 50% of the slaves as well, which is 4% smaller than $\text{Max}(p_{\text{cat}})$ method.

![Figure.6.15](image-url)

**Figure.6.15** Performance in terms of discovery time and discovery rate and probability of collision-avoiding-transmission as functions of transmission probability without stopping criteria, when number of PDR is 16. The discovery time for the $p_r$ which maximize the $p_{\text{cat}}$ is very close to the minimal discovery time.

In this sense, the area above each curve corresponds to the total proportion of the discovered pairs in one frame. It is obvious that the area for red curve is larger than the blue one in that the aim of $\text{Max}(#dp)$ method is to maximize this area. However, we use the proportion of slaves which have discovered the master (e.g. the dashed line of $T=50\%$ shown in Figure.6.14) to evaluate discovery. We can see clearly in the figure that the quantity of masters which are discovered by at most 50% slaves (the points indicated in Figure.6.14) for $\text{Max}(p_{\text{cat}})$ method (6%)
is larger than that of $Max(\#dp)$ method (2%), which implies more discovered masters (4%) in one frame for $Max(p_{cat})$ method.

The reason for this is the $Max(\#dp)$ method distributes the discovered pairs more evenly across the masters, since 50% of the masters are discovered by at least 1 slaves, but the masters which are discovered by at least 50% of slaves is only 2%. On contrary, the $Max(p_{cat})$ method concentrates the discovered pairs to 17% of the masters, and the discovered masters (6%) triple that of the $Max(\#dp)$ method. Therefore, the $Max(p_{cat})$ method works with a higher efficiency than the $Max(\#dp)$ method, and the discovery time for it is very close to the optimum.

Subsequently, we study on how much difference between the optimal method of setting $p_{tr}$ which minimizes the discovery time with guaranteed discovery rate and the $Max(p_{cat})$ one. In Figure.6.15, we can find the relationship between the value of $p_{cat}$ and discovery time. The discovery time for the $p_{tr}$ corresponding to the peak of $p_{cat}$ curve is only a little bit larger than the optimal one. The difference of performance in terms of discovery time between the method of $Max(p_{cat})$ and the optimum for different number of masters can be found in Figure.6.16. This difference becomes larger with the increasing of the number of masters, but still not very large. Therefore, the performance of $Max(p_{cat})$ method is always good (only a little bit worse than the optimum in terms of discovery time), added with the lower complexity to achieve, this suboptimal method is practical.

![Figure 6.15](image1.png)

**Figure 6.15** The difference of the performance between the $Max(p_{cat})$ method and the optimal one in terms of discovery time, as a function of number of masters, for the case of fixed transmission probability without stopping criteria. The larger the number of masters, the larger the difference in discovery time, but not much overall.

### 6.2.3. Scenario A2 (NAL2): Fixed $p_{tr}$ with Stopping Criteria

In this scenario, the information about the quantity of slaves is available, and the paging signals can be sent back to masters to inform discovery, so we can introduce stopping criteria with this
level of network assistance. However, the information of number of active masters is only available in the beginning of discovery process, so the masters are not able to know the progress of the discovery, and then they can just use fixed $p_{tr}$. The optimal $p_{tr}$ is the one which minimizes the discovery time with guaranteed discovery rate, which only can be obtained from the simulation results for different cases, so the masters have to save the results and keep on using the same $p_{tr}$. Since the number of active masters decreases with the time, the performance with the $p_{tr}$ which performs well in the beginning of the process (method with Formula (8)) can become poor in the rest of the process. We just take it as the non-optimal one, which is used for comparing with the optimum.

![Graphs showing performance metrics](image)

**Figure 6.17** The performance of Scenario A2, in terms of discovered masters with time as well as discovery rate and energy consumption. The performance of the optimal one is in terms of minimizing the discovery time with guaranteed discovery rate, while the non-optimal one uses the $p_{tr}$ which is the best just in the beginning and unchanged during the whole discovery process. The discovery time of the non-optimum outperforms the optimum in the first half of the process, and then is overtaken by the optimum in the second half of the process.

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One thing we need to mention here is that the optimal $p_r$ is the optimum for the whole process, so it is not necessarily the best in all phases. The number of PDRs is still 16. We can see in Figure.6.17 that for the first half of the process, the non-optimal one outperforms the optimal one in terms of the discovery time, for the reason that the non-optimal one is designed for 100 active masters, so it performs well in the beginning. However, in the rest of process, the optimal one works with high efficiency, and overtakes the non-optimum finally. Nevertheless, the discovery rate for the non-optimal one is a bit higher than the optimal one. As a consequence, the optimal fixed $p_r$ has the best performance during the whole process.

6.2.4. Scenario A3 (NAL3): Adaptive $p_r$ with SC

![Graphs showing performance comparison](image)

Figure 6.18 The performance of Scenario A3, in terms of discovered masters with time as well as discovery rate and energy consumption. The performance of the Max($p_{cat}$) method is better than Max(#dp) one in all aspects.

In this scenario, the network broadcasts the updated information on the number of active masters in the cell continuously (the active masters send a signal to the network when it reaches its
stopping criteria, so the network knows the updated number of active masters). Taking advantage of this updated information, the masters can adapt the $p_{tr}$ to keep the load of the system in a reasonable range, and then to make the discovery process proceeding with high efficiency, in terms of reducing the collision probability and saving energy consumption.

Regardless the most complex optimal method, we have another two methods of $\text{Max}(p_{cat})$ and $\text{Max}(#dp)$ for setting the adaptive $p_{tr}$. The corresponding $p_{tr}$ for these two methods can be found from Figure.6.6. In reality, from complex and practical perspective, the $\text{Max}(#dp)$ method requires the masters store the table of $p_{tr}$ according to different number of masters for different cases, so the masters search for the right $p_{tr}$ with the updated information on the number of active masters from the table. However, for the $\text{Max}(p_{cat})$ method, it is easier to calculate $p_{tr}$ in real-time instead of saving a table and searching for the matched one each time.

The number of PDRs is still 16. It can be seen from the first subplot of Figure.6.18 that the discovered masters as a function of time for the $\text{Max}(p_{cat})$ method is almost linear, which
indicates the $p_{tr}$ is appropriate during the whole discovery process. It is obvious that the performance of $Max(p_{cat})$ method is better than that of $Max(#dp)$ one in all aspects. On the other hand, since the $p_{tr}$ is updated continuously in this scenario, the low complexity becomes another advantage for the method of $Max(p_{cat})$ to be the optimal option in the adaptive $p_{tr}$ scenarios.

### 6.2.5. Scenario A4 (NAL4): Unicast PDR

In this scenario, the network unicasts specific PDR to each master, which is the most effective way in D2D discovery. The masters do not need to design transmission probability by themselves, instead of which they only listen to the command from the network. At lower levels of network assistance discussed previously, the network could help with setting transmission probability to reduce the collision probability. However, the collision can be completely avoided with NAL4. At this level, everything is well managed by the network, and the performance of it can be seen in Figure 6.19. The number of PDR is still 16.

On the other hand, the cost of signaling increases at this level, because the network has to communicate with all the masters separately and make scheduling for them. Also, NAL4 assigns orthogonal resources to masters so that spatial reuse of PDRs is not achieved in this scenario. We do not consider the cost of the signaling in this work, but it is a very important factor in reality, so the cost-effectiveness for different levels of network assistance will be studied in the future work.

### 6.2.6. Comparison among Different Time Priority Scenarios

The performance of scenario AX with different levels of network assistance is compared in this section. By and large, the discovery time and energy consumption for both masters and slaves are reduced with higher level of network assistance. We can also achieve better discovery rate with higher level of network assistance except NAL2. However, the difference of performance is not proportional to the difference of complexity between adjacent network assistance levels.

From NAL0 to NAL1, the number of masters is available in the beginning of D2D discovery process, so the option for setting $p_{tr}$ becomes more reasonable, and the improvement from this is large. However, without stopping criteria, both of the scenarios work with low efficiency. It is like the Coupon Collection Problem described in [5] that, the “last” several undiscovered masters lead to much more time to be discovered by enough ($T=50\%$ in this work) slaves than the masters that get discovered first. Because the masters cannot detect whether they have been discovered, they keep on sending beacon signals. In the simulation, we can easily calculate the time when all the masters have been discovered by more than $T$ of the slaves, but in reality, the masters in these two levels cannot know if they have been discovered, so the discovery process goes on.

In order to increase the resolution of the other curves, we do not show the tail of the curves for A0 and A1 in Figure 6.20. Actually, there is some difference in discovery time between these two levels, and this gap can be even larger with increasing of the number of active masters in the cell.
Figure 6.6: Performance comparison among Time Priority Scenarios with different levels of network assistance, in terms of discovered masters with time as well as discovery rate and energy consumption. Shorter discovery time can be achieved from higher network assistance levels, and the discovery rates are quite similar for different levels. Generally, higher level of network assistance indicates lower energy consumption for both masters and slaves (the cost of paging signals and the signals between eNB and devices is not considered), but not always.

From NAL1 to NAL2, the number of slaves is available and the paging from slaves is active. Accordingly, we can introduce stopping criteria at this level. From Figure 6.20, we can see the improvement in discovery time for NAL2 from the lower two levels is significant, which indicates the stopping criteria can largely improve the performance in D2D discovery. However, without the updated number of active masters continuously, the masters can only use fixed $p_r$. The performance for this level is not very good in the beginning, which is even worse than the lower two levels. The reason is obviously that the relatively high $p_r$ in the beginning leads to the high load of the system. As the discovery proceeds, more masters are muted with stopping criteria, and then the system works with high efficiency. What is noticeable, the discovery rate for NAL2 is a little bit lower than the other levels, but still acceptable.
From NAL2 to NAL3, the information about number of active masters is available continuously, and then we can use adaptive $p_t$. In Figure 6.20, we cannot obtain much benefit in discovery time and discovery rate with adaptive $p_t$. However, the mechanism for adaptive $p_t$ is more complicated than the fixed one. In consequence, it may be not very well worth to use adaptive $p_t$.

From NAL3 to NAL4, the improvement for the highest level of network assistance is notable in all aspects, all the pairs which can achieve discovery will get discovery at this level, although it costs even more signaling. In NAL4, the network takes responsibility for all the devices, which consumes the signaling resources much.

In summary, the D2D discovery can indeed benefit from the network assistance. Figure 6.20 gives us an intuitive impression on the performance comparison of different network assistance levels. A more accurate comparison about the numerical results can be found in the following table.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Discovery time (s)</th>
<th>Discovery rate (%)</th>
<th>Energy consumption of masters (J)</th>
<th>Energy consumption of slaves (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>75.92 (100%)</td>
<td>69.7</td>
<td>0.191 (100%)</td>
<td>3.344 (100%)</td>
</tr>
<tr>
<td>A1</td>
<td>64.58 (85.1%)</td>
<td>69.7</td>
<td>0.260 (136%)</td>
<td>2.860 (85.5%)</td>
</tr>
<tr>
<td>A2</td>
<td>20.62 (27.2%)</td>
<td>64.2</td>
<td>0.133 (69.6%)</td>
<td>0.907 (27.1%)</td>
</tr>
<tr>
<td>A3</td>
<td>15.01 (19.8%)</td>
<td>67.0</td>
<td>0.055 (28.8%)</td>
<td>0.660 (19.7%)</td>
</tr>
<tr>
<td>A4</td>
<td>7.00 (9.2%)</td>
<td>70.0</td>
<td>0.025 (13.1%)</td>
<td>0.308 (9.2%)</td>
</tr>
</tbody>
</table>

Table 5 presents the quantitative performance related to different network assistance levels. The better performance can be always obtained with higher level of network assistance, which is consistent to the graphical results. Since the discovery rates with different network assistance levels are quite similar, we assume the discovery time and energy consumption for Scenario A0 to be 100%, and then the percentage for the other levels can be calculated as well and easily to be compared mutually.

We can say that about 91% of the discovery time can be saved from the highest level of network assistance to the lowest level, while the discovery rates do not fluctuate much. Much energy consumption can also be saved from network assistance at both the sides of masters and slaves, up to 87% and 91% separately. All these results give us a very optimistic application prospect for the cellular network assistance in the D2D discovery.

Additionally, we just take 100 active masters as an example to investigate in the area of study, which is not many compared with the real world. With more and more types of devices join into the D2D communication system, the quantity of devices will be increased dramatically. However, the approaches of study and mechanism described in this work are still efficient, and the impact of cellular network assistance can become bigger with more devices.

On the other hand, we also compare the energy consumption of masters and slaves in the process of D2D discovery with the battery capacity of them. We find that the energy consumed by the
devices (e.g. mobile phone) for D2D discovery is very small compared with the battery capacity of them, which can be found in the table of Appendix.A.

### 6.2.7. Comparison between Scenario AX and BX

The difference between Scenario AX and BX is that the masters and slaves are merged into one type of nodes in Scenario BX, so when one device transmits, it cannot listen to the PDRs in the same time slot as it uses. As a result, it misses some beacon signals from other devices, which may prolong the discovery time or lower the discovery rate. From the example for scenario A1 and B1 expressed in Figure.6.21, we can see that the difference between Scenario AX and BX is quite slight, regardless of the number of PDRs.

![Graphs showing comparison between Scenario AX and BX](image)

*Figure.6.21 Performance comparison between Time Priority Scenario AX and BX, in terms of discovery time, discovery rate and energy consumption as a function of number of PDRs. The difference between scenario AX and BX is very slight.*
6.3. **Energy Limited Discovery Scenarios**

In the Energy Limited Scenario, the energy budget is taken into account. Therefore, the transmission power cannot be set to the maximum directly. Generally, higher transmission power indicates larger coverage of the masters, but in a high collision case, even high power cannot get good performance as well. From another perspective, transmitting for more times can increase the opportunity of transmission without a collision. There is thus a trade-off between the transmission power and times within the energy budget. How to set the transmission power and how much improvement can be obtained from the network assistance in Energy Limited Scenario is investigated in this section.

6.3.1. **Scenario C1**

![Figure 6.22 Schemes of power setting for the Energy Limited Scenario. Scheme 1 uses maximal transmission power for once, Scheme 2 uses half of the maximal power for twice and Scheme 3 uses a quarter of the maximal power for four times.](image)

In order to find the rules for power setting, we compare three schemes with same energy budget of $C=24\text{dbm}*1\text{ms}$ for four frames totally. With this constraint, the masters can only transmit for very limited times, so the quantity of discovered pairs is limited as well. The masters still want to be discovered by as many slaves as possible, so in Energy Limited Scenario, we can use discovery rate (percentage of pairs which SINRs exceed 1 dB, assume the decoding threshold of SINR is 1 dB) to evaluate the performance. The CDF of SNR implies the limitation of potential pairs which can get discovery (SNRs exceed 1 dB), while the CDF of SINR shows the proportion of discovered pairs (SINRs exceed 1 dB) to the totally number of potential pairs after the discovery process. Assume the number of PDRs is 25 in Energy Limited Scenario.

Since the number of transmitting times is quite limited in Energy Limited Scenario, there is no need to use the concept of transmission probability. We define three schemes in Scenario C1, which are provided with only NAL0. In scheme 1, the masters use full maximal power to transmit for once in one of the four frames, while in scheme 2, the masters use half of the maximal power to transmit for twice in two of the four frames. Similarly in the third scheme, the masters use a quarter of the full power to transmit for four times in each of the PDR frames, which can be found in Figure.6.22.

From the left subplot of Figure.6.23, we can see the percentage of pairs which SNRs exceed 1 dB (the pairs can get discovery if there is no collision) for scheme 1 is larger than the other two, due to the higher transmission power. Then it is clear in the right subplot of Figure.6.23 that the proportion of discovered pairs (SINRs exceed 1 dB) for scheme 1 is still larger than the other two,
because of the lower collision probability and the larger coverage of the masters. Therefore, we can draw the conclusion that in Energy Limited Scenario, transmitting with higher power for fewer times is better than that with lower power for more times.

Figure 6.23 CDF of SNR and SINR for different schemes in Energy Limited Scenario indicates that transmitting with higher power for fewer times (Scheme 1) can achieve a better discovery rate than that with lower power for more times.

6.3.2. Scenario C2 and Compared with Scenario C1

Figure 6.24 Comparison of discovery rate (the proportion of pairs which SINRs exceed 1dB) for different Energy Limited Scenarios.
In the Energy Limited Scenario C2, we assume that the network can unicast the PDRs to each master (NAL4), which is similar as Scenario A4. From Figure 6.24, we can see the discovery rate (percentage of pairs which SINRs exceed 1 dB) for different Energy Limited Scenarios. In Scenario C1, only around 45% pairs can get discovery while in Scenario C2 more than 70% pairs can achieve discovery. In conclusion, the network assistance can also help much in the energy limited scenarios in D2D discovery.
7. Conclusions

This work is addressed on the role of cellular network in the D2D discovery process, and we distinguish the network assistance into 5 levels. In the Time Priority Scenarios of D2D discovery, the performance in terms of discovery time, discovery rate and energy consumption can benefit from different levels of the cellular network assistance. Numerical results indicate that, to reach a given level of discovery rate, up to 91% discovery time and energy consumption for slaves and 87% of the energy consumption for masters can be reduced with highest network assistance level compared with the lowest one. However, the effect and complexity are disproportionate with difference level of network assistance.

- The available information on the number of active masters in the cell can significantly improve the performance.
- Stopping criteria can obviously increase the efficiency of the system.
- The benefit of using adaptive transmission probability from the fixed one is not much.
- Unicasting PDR is the most effective approach, but it costs more signaling resource.

In the Energy Limited Scenarios, within certain energy budget, the cellular network assistance can improve the performance of discovery in terms of the discovery rate (around 23%).

- Transmitting with high power for fewer times is better than using low power for more times.

If a fixed transmission probability is used, there is an optimal option for it, in terms of the minimal discovery time with guaranteed discovery rate. Whereas, if the transmission probability is adaptive according to the load of the system, the method of maximizing probability of collision-avoiding-transmission outperforms the one that maximizing the average number of discovered pairs in one frame. The performance of the former one is very close to the optimum and is easy to achieve in reality.

The difference of performance between separate and merged type of nodes are very slight. Moreover, if the thresholds are set properly, Single Stopping Criteria (SSC) works better than Alternative Stopping Criteria (ASC) in almost of the cases, especially when the probability of collision is high. Additionally, the decrement in slave active probability does not always save the energy consumption for slaves, but depraves the performance in discovery time, discovery rate and energy consumption for masters.

Gain in discovery time and energy consumption can be obtained when more PDRs are used. However, according to a given fixed transmission probability, there is a threshold for the quantity of PDR to achieve the same performance. The improvement is not noticeable when the quantity of PDRs exceeds this threshold. Therefore, not all of the PDRs in PDR frames are necessary to be used in some cases. When the probability of collision is high, using single PDR is better than multiple PDRs, while the probability of collision becomes low, using multiple PDRs outweighs the single one.

In summary, the cellular network can assist with reducing the discovery time, guaranteeing the discovery rate and saving energy consumption in both the Time Priority Scenarios and Energy Limited Scenarios of the D2D discovery.
8. Future Work

We emphasize the role of cellular network in the D2D discovery phase for D2D communication in this work, and many factors with respect to this are investigated as well. During the process of study, we find many interesting topics worth further studying based on this work. Due to the time limitation, we only list them as the future work.

The network assistance is distinguished into 5 levels in this work, but the positioning information is not included in these 5 levels. If several potential pairs are far away from each other, they can reuse the same PDR to transmit their beacon signals, without yielding much interference to each other. In addition, it also increases the usage of PDRs. However, the availability of positioning information brings more cost to the system, so whether it is worth using positioning information in the D2D discovery phase and how to use it can be an interesting topic in the future.

We present three methods for setting transmission probability fixedly or adaptively in this work, and we find that maximizing $\tilde{p}_{cat}$ is a practical method for setting the transmission probability adaptively according to the load of the system. Although we prove that it is very close to the optimal one, there is still some improvement can be obtained with the optimal method, which can be approached by formulating a Markovian Decision Process (MDP). Future research can be explored on it.

Additionally, we demonstrate that using multiple PDRs for transmitting masters in sufficient PDR case can save discovery time. We give out two schemes in multiple PDRs selection, but they are only examples of using multiple PDRs. Whether there is a better scheme and how to design the multiple PDR selection are still need to be studied in the future.

We only take the energy consumption of beacon signals into account in this work. The cost of paging signals and the signals between the devices and network is not counted. Although the performance of some scenarios is good, if the cost for achieving them is also high, then it is still not a proper option from practical perspective. Therefore, we should consider the cost of signaling related to different levels of network assistance, and find out the highest cost-effective one in the future work.

Finally, it is proven that using stopping criteria can largely improve the performance in the D2D discovery phase, and the thresholds for the conditions of stopping criteria can also influence much on the efficiency and quality of discovery. For example, if the threshold for SSC is set too high, the discovery process cannot stop. We leave some margin for the threshold setting of stopping criteria in this work, but how to find the scientific way of setting it still needs further study.
Appendix.A. Energy Consumption and Battery Capacity for Mobile Phone

The following Table.A.1 is about the proportion of energy consumption of devices for both masters and slaves in D2D discovery to the battery capacity of some model of mobiles. The energy consumption for a device acts as a master or a slave is different. Since the largest proportion is $1.8*10^{-6}$, all of the energy consumption for the devices is tiny compared with the battery capacity. Therefore, the mobile phones can be considered to work in the Time Priority Scenarios.

Table.A.1 Proportion of energy consumption to the battery capacity

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Mobile model (Battery model)</th>
<th>Energy Consumption in the whole discovery process</th>
<th>Battery capacity</th>
<th>Energy Consumption</th>
<th>Battery capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>Nokia Lumia 800 (BV-5JW)</td>
<td>9.9*10^{-8}</td>
<td>19.3kJ (3.7V, 1450mAh)</td>
<td>1.0*10^{-7}</td>
<td>8.4*10^{-8}</td>
</tr>
<tr>
<td>A0</td>
<td>iphone 4S (Specific)</td>
<td>1.8*10^{-6}</td>
<td>18.9kJ (3.7V, 1420mAh)</td>
<td>1.8*10^{-6}</td>
<td>1.5*10^{-6}</td>
</tr>
<tr>
<td>A0</td>
<td>Sony Xperia S LT26i (Specific)</td>
<td>1.5*10^{-7}</td>
<td>22.7kJ (3.7V, 1750mAh)</td>
<td>1.5*10^{-7}</td>
<td>1.3*10^{-7}</td>
</tr>
<tr>
<td>A1</td>
<td>Work as a master 0.00191 J</td>
<td>8.2*10^{-8}</td>
<td>1.0*10^{-7}</td>
<td>8.4*10^{-8}</td>
<td>7.0*10^{-8}</td>
</tr>
<tr>
<td>A1</td>
<td>Work as a slave 0.00344 J</td>
<td>1.3*10^{-7}</td>
<td>1.4*10^{-7}</td>
<td>1.1*10^{-7}</td>
<td>1.3*10^{-7}</td>
</tr>
<tr>
<td>A2</td>
<td>Work as a master 0.00260 J</td>
<td>2.8*10^{-8}</td>
<td>1.5*10^{-7}</td>
<td>2.4*10^{-8}</td>
<td>2.9*10^{-7}</td>
</tr>
<tr>
<td>A2</td>
<td>Work as a slave 0.00935 J</td>
<td>4.8*10^{-7}</td>
<td>5.0*10^{-7}</td>
<td>4.1*10^{-7}</td>
<td>4.1*10^{-7}</td>
</tr>
<tr>
<td>A3</td>
<td>Work as a master 0.00055 J</td>
<td>3.4*10^{-7}</td>
<td>2.9*10^{-8}</td>
<td>2.4*10^{-8}</td>
<td>2.9*10^{-7}</td>
</tr>
<tr>
<td>A3</td>
<td>Work as a slave 0.00660 J</td>
<td>1.3*10^{-8}</td>
<td>3.5*10^{-7}</td>
<td>1.1*10^{-8}</td>
<td>1.4*10^{-7}</td>
</tr>
<tr>
<td>A4</td>
<td>Work as a master 0.00305 J</td>
<td>1.6*10^{-7}</td>
<td>1.6*10^{-7}</td>
<td>1.4*10^{-7}</td>
<td>1.4*10^{-7}</td>
</tr>
</tbody>
</table>

Appendix.B. Derivation of $p_{collision}$ and $p_{cat}$ for Multiple PDR Selection Schemes

First, we assume the PDRs selection for different masters are independent from each other. When the masters use multiple PDRs to transmit multiple beacon signals in discovery phase, the probability of collision in each PDR for a given master is same for both scheme 1 and 2.
(Figure 5.1). Thus we define $p_{col-sp}$ as the probability of collision in a single PDR, and $n$ is the number of multiple PDRs used each time. Also, $L$ and $M$ are the number of PDRs in time domain and frequency domain separately in the PDR frame (there are $M \times L$ PDRs in one PDR frame). Then we can find more general expressions for the probability of collision and the probability of collision-avoiding-transmission for both scheme 1 and 2 of the multiple PDRs selection case.

In Scheme 1, $\binom{L}{n} \cdot M^i$ is the total number of possible patterns for the multiple PDRs selection, and then $\binom{L-1}{n-1} \cdot M^{i-1}$ express the number of possible patterns for another master also selects this PDR to transmit, so we can get the probability of collision in one of the $n$ used PDRs for master $i$ that:

$$p_{col-sp(i)} = 1 - \prod_{j \neq i} \left( 1 - p(A_j) \cdot \frac{\binom{L-1}{n-1} \cdot M^{i-1}}{\binom{L}{n} \cdot M^i} \right) = 1 - \prod_{j \neq i} \left( 1 - p(A_i) \cdot \frac{n}{L \cdot M} \right) = 1 - \left( 1 - p(A_i) \cdot \frac{n}{L \cdot M} \right)^{N_{\text{master}} - 1} \forall i.$$  

(B1)

Then, following the Binomial distribution, we can derive the probability of collision for master $i$, which indicates the probability that all the $n$ PDRs used by master $i$ collide with others.

$$p_{\text{collision}}(i) = \binom{n}{1} \cdot p_{col-sp(i)} \cdot (1 - p_{col-sp(i)})^0 = p_{col-sp(i)}^n \forall i.$$  

(B2)

Moreover, the probability of collision-avoiding-transmission for master $i$ can be expressed as follows:

$$p_{\text{cat}}(i) = p(A_i) \left( 1 - p_{\text{collision}}(i) \right) = p(A_i) \left( 1 - \left( 1 - p(A_i) \cdot \frac{n}{L \cdot M} \right)^{N_{\text{master}} - 1} \right)^n \forall i.$$  

(B3)

Consequently, the average probability of collision-avoiding-transmission over all the masters in the multiple PDRs selection is as:

$$\bar{p}_{\text{cat}} = \frac{1}{N_{\text{master}}} \sum_{i} p_{\text{cat}}(i) = p(A_i) \left( 1 - \left( 1 - p(A_i) \cdot \frac{n}{L \cdot M} \right)^{N_{\text{master}} - 1} \right)^n \forall i.$$  

(B4)

In scheme 2, the PDR frame is divided into $n$ blocks, and the master transmits one beacon signal in each block of the PDR frame, so it is avoided automatically that more than one PDR in the same PDR time slot is picked simultaneously by a master.

Similarly, the $p_{col-sp}$ for scheme 2 can be calculated is as follows:

$$p_{col-sp(i)} = 1 - \prod_{j \neq i} \left( 1 - p(A_j) \cdot \frac{1}{L \cdot M} \right) = 1 - \prod_{j \neq i} \left( 1 - p(A_i) \cdot \frac{n}{L \cdot M} \right) = 1 - \left( 1 - p(A_i) \cdot \frac{n}{L \cdot M} \right)^{N_{\text{master}} - 1} \forall i.$$  

(B5)

the result of which is same as scheme 1. Then, the calculation about the probability of collision and the probability of collision-avoiding-transmission are consistent with Formula (B2)-(B4). Therefore, the performance of scheme 1 and 2 are exactly the same. When we insert $n=1$ to Formula (B2)-(B4), they are degenerated to the single PDR case, which are exactly the same as Formula (5)-(7).
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References


