The application of D2D communication in 60 GHz millimeter wave transmissions

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Abstract

Motivated by the increase of traffic load in cellular network and the associated increase of traffic through the network, device-to-device (D2D) communication with 60GHz millimeter wave (mmWave) is a possible solution to manage this future task. In this research project, our investigation focuses on the benefits of combining D2D links and conventional links with 60 GHz mmWave.

Our investigation is performed in two phases. At first, we consider a network that has only two users, to provide a better understanding of the performance of different communication schemes with 60 GHz mmWave in simplified circumstances. Subsequently, from the realistic point of view, a multi-users system is introduced in latter to detect the relation between system throughput, antenna beamwidth, and interference model. Meanwhile, to ensure the accuracy of system performance, an accuracy improvement algorithm based on iterative algorithm is purposed in the project either.

Simulation results show that, the system with D2D communication and conventional communication together improves performance of system with pure conventional system under 60 GHz mmWave. The capacity can improve more than 13 times with 60 GHz mmWave under highly directional antenna compared with 5 GHz transmission, and system performance highly depends on antenna beamwidth and traffic load. Meanwhile, interference analysis indicates that the interference is not a significant factor for 60 GHz mmWave communication. Finally, the ratio for D2D links under different propagation conditions describes the appropriate environment of using D2D communication in network.

Key words: 60 GHz millimetre wave, D2D communication, antenna beamwidth, traffic load, Interference analysis, and accuracy improvement algorithm.
Sammanfattning

Motiverad av ökningen i mobila nätverks trafikbelastning samt även den relaterade trafiken genom nätverket. Detta projekt fokuserar på fördelarna med nätverk kombinerat D2D och konventionella länkar med 60 GHz mmWave att hantera denna framtida uppgift. Vår undersökning utförs i två faser. Först föreställer vi oss ett nätverk som endast har två användare, för att bättre förstå olika kommunikationssystem genomförda omständigheter. Därefter, från den realistiska synvinkeln, är ett multi-användar system introducerat för att undersöka förhållandet mellan systemets antennbandbredd och störningar. Simuleringsresultat visar att kapaciteten kan förbättras mer än 13 gånger med 60GHz mmWave under en mycket riktad antenn jämfört med 5GHz överföring, och systemets prestanda är mycket beroende av antennens bandbredd och trafikbelastning. Samtidigt indikerar störningsanalys att störningen inte är en signifikant faktor för 60 GHz mmWave.
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Chapter I: Introduction

The mobile market was growing significantly in last few years, the trend also points out that a tremendous increase can be expected during the upcoming years. The radio spectrum band used previously mainly focuses on UHF (Ultra high frequency) or VHF (Very high frequency) [1] [2]. However, these specific spectrums are more and more crowded since the growth of data requirements. Under this occasion, it is necessary to develop an advanced communication technology to adapt the increasing demands.

In this paper, the technology of 60 GHz mmWave and D2D communication is adapted simultaneously to improve the system performance. Meanwhile, the influence of the variety of traffic load and antenna beamwidth on system performance is derived through the simulations. Finally, the performance comparison of ideal antenna and general antenna is also studied in this paper either.

Chapter II and III show the structure and basic methods used to construct the scenario. Chapter IV describes the numerical and graphical results and the analysis of the results. Finally, Chapter V and IV describe the conclusion and introduce future work of this project.

1.1 Motivations for 60 GHz millimeter wave

The large variety of application shows that the real-time traffic with large varying delay constraints as well as non-real-time traffic with different reliability requirements should be implemented in wireless infrastructure [3]. To satisfy these requirements, increasing spectrum efficiency or available bandwidth are both useful methods. The available frequency bandwidth for 60 GHz is much higher compared with conventional communication like 5 GHz, which generates some specific characteristics for the propagation of 60 GHz mmWave. On the one hand, 60 GHz mmWave has an unlicensed spectrum with 7 GHz available frequency bandwidth to transmit the data packet which makes the maximum bit rate can achieve 2G bps more [4], this means the data requirements can be satisfied with increasing traffic. On the other hand, 60 GHz communication has a sever path loss to affect the performance of system.

In wireless communication, the throughput of the communication link is one of the most important indicators to estimate the performance. The throughput, however, highly depends on the characteristic of propagation channel, like path loss, distance
between devices, the noise, etc. Through the formula of Friis free space path loss model, the path loss for 60 GHz has a nearly 28 dB loss more versus the 5 GHz mmWave. Meanwhile, additional loss (7-15.5 dB/km power loss) needs to be considered in the received signal at 60 GHz carrier frequencies because of atmospheric absorption [5]. Besides these, rainfall rate also affects the performance of the system. Around 8-18 dB/km additional atmospheric attenuation while the rainfall rate is 50 mm per hour [5]. In addition to the high attenuation, 60 GHz mmWave radio also experiences the weak capability of penetration (Seen in the Table 1.1) [6].

After considering all kinds of attenuation, the path loss for 60 GHz model is finally determined [7] (Described in section 3.2.2). Although the handicaps thwart the development of 60 GHz mmWave communications, there are still some advantages attracting people to research in this area. Highly directional antennas can be used to reduce multipath effects by limiting the azimuth and elevation angular range from which radiation is emitted and captured [6]. With the thought on the tradeoffs in modulation, equalization, antennas technology, 60 GHz mmWave is a useful technology to improve the system performance.

### 1.2 Description of D2D communication

Device-to-Device (D2D) communication is an efficient way to enhance the spectrum use. Compared with the method like increasing the available spectrum or shrinking the cell range, D2D communication is a solution with high performance cost ratio. In D2D communications, data packets can be transmitted between two users directly when two users are close to each other. This would theoretically result in decreasing of the traffic over the eNBs and provide a better user experience in terms of traffic throughput enlarging [8].

According to the study by Fernando J [10], where the similarities and differences of 40 GHz and 60 GHz mmWave are integrated, the propagation parameters and conditions for D2D link in 60 GHz mmWave transmission are finally determined. Meanwhile, the noise in propagation channel is also determined from the study of Joongheon Kim [9].
Chapter II: Investigation on System Benefit

2.1 Objective and Methodology

As mentioned in the introduction, the benefit of D2D link with 60 GHz mmWave is investigated in this paper. Since the system throughput plays an important role to measure the performance of network, the throughput of network by using D2D communication with 60 GHz mmWave under different conditions, like different traffic load or antenna beamwidth are studied either. Finally, the comparison between systems with different interference models is also shown in this paper. In light of above, the main idea of our research is the performance of network by adapting D2D communication and conventional communication simultaneously with 60 GHz mmWave. The aspects under investigation are summarized as follows:

- The cumulative distribution function (CDF) of system throughput, as the D2D communication with 60 GHz mmWave is implemented.
- The relation between system throughput, traffic load, and antenna beamwidth in multi-users network with 60 GHz system.
- The difference of system performance with ideal antenna and general antenna.
- The impact of difference interference model on system throughput.
- The ratio that D2D communication is adapted in system under different conditions.

2.2 Preliminary

To detect the performance of system adapted D2D communication under 60 GHz mmWave with highly directional antenna. At first, we consider a simple network infrastructure with only one single cell which is hosting only two users (one communication link), (see figure 2.1). The purpose is to find when a link established in the network, the probability that the performance of D2D link is better than the conventional communication. It is a simple case to familiar with the characteristic of 60 GHz mmWave and the performance of D2D and conventional link. Detailed description is shown in section 2.3.
Based on the characteristics of 60 GHz mmWave, in the following step, a more complicated scenario is discussed, which multi-users are generated in a single cell, and the central controller can assign the communication scheme for each link according to maximum system performance under different environment conditions, Figure 2.2 shows the structure of this scenario.

2.3 Description of Single Link System

In the network, since the 60 GHz mmWave focuses on short distance communications
due to the high oxygen attenuation and high path loss, mmWave base stations are uniformly deployed on the cell edge [11]. Meanwhile, for the simplicity, only two users are randomly distributed in the system [12], as Figure 2.1 shows. Here, we consider the signal to noise ratio (SNR), which directly relates to the system throughput.

In network, central controller determines the communication scheme adapted in each link, the performance of D2D and conventional communication with 60 GHZ mmWave is discussed in advance. To get a more accurate performance comparison, we use CDF plots (results for 10000 simulations) to show the distribution of system throughput under different conditions. With these plots, it is easy to see the change of the performance and analysis the advantages and disadvantages in different communication systems. Then, in D2D communication system, the relative distance between two users, directly effects the performance of throughput, this relation of distance and throughput is also given in the paper. Finally, the relation of LOS and NLOS propagation conditions is derived in this part either.

In each simulation, once two users are randomly generated in the cell, the device will not shift its location which means the distance between two users and relatively base stations are fixed, by using specific path loss model, the path loss of D2D link and conventional link can be obtained. In normal, The SNR of the link is given by:

$$ SNR = \frac{P_{\text{signal}}}{P_{\text{noise}}} $$

There are two main reasons make us use parameter SNR instead of using Signal-to-interference-plus-noise ratio (SINR). On the one hand, by using highly directional antenna, the transmission is almost “pseudowired” [13]. On the other hand, since there are only two users in the cell, the interference caused by other links does not exist.

Given the transmitting power, antenna gains and path loss, the received power in dB scale is shown as

$$ P_{\text{received}}^{\text{dB}} = P_t + G_r + G_t - L_p. $$

### 2.4 Description of Multi-Users System

In this scenario, we increase the number of links (communication pairs) in network, as shown in Figure 2.2, and recalculate the system throughput to find the relation between system throughput and important factors that may influence performance. Meanwhile, ideal antenna and general antenna model are also implemented in system to find the difference caused by sidelobe(s). Finally, we evaluate the influence of
interferences by using two communication schemes and the impact of D2D communication in 60 GHz mmWave transmissions.

For multi-users network with technology like 5 GHz mmWave transmission, the interference caused by other communication pairs is a significant factor influencing the capacity of system. In 60 GHz mmWave technologies, with MIMO antenna arrays and highly directional antennas, the interference can be minimized. However, since the D2D communication scheme adapted in our system, the interference situation should reconsidered since it is different than before. The analysis of performance of multi-users network by using combining schemes can be divided into three parts.

- First of all, we discuss the influence of interference model for the system. Figure 2.3 shows four different types of interference may occur in the system with ideal antenna. Each model happens occasionally according to the location and the direction of antenna beamwidth of the device. To derive the impact of interference, two interference models are used to compare:
  - Only D2D pair Interferes D2D pair (DID) model;
  - Aggregated interference (AI) model (include all four kinds of interference).

The antenna beamwidth of transmitter from interfered links is pointing to the receiver of target link indicates the interference generated in the system. As for general antenna, the interference generated by sidelobe(s) of antenna is also considered. Considering system with AI model needs to use more resource in calculation, we want to find difference of system performance with two kinds of model, if the difference is not so big, DID model is more suitable since the calculation is not as complex as AI model.

- Then, since antenna beamwidth and traffic load are important factors for the network, the relation between these parameters and system throughput is derived through the simulations. With ideal and general antenna scenario, the CDF of system performance is derived to analyze whether the relation changes in these two different situations. Meanwhile, the impact of antenna radiation efficiency is also derived through the experiments.

- Finally, since D2D communication is adapted in the system to improve system throughput, the probability that D2D scheme is assigned for links is derived in the experiments. Meanwhile, as the parameters like antenna beamwidth and traffic load change, observe whether this probability changes either.
Figure 2.3: Interference Model with aggregated interference
Chapter III: System Models

3.1 Overview

The procedure of this project is based on three basic steps, starting from the literature review, then simulation, and finally the data analysis. The first step to start the thesis is doing research on the website and reading papers from IEEE and relative articles, then determine the subject of purpose and find the field that is interested in to work on.

After have a roughly idea of the implementation on the focused area, start setting up experiments to identify the ideas determined through the literature review in step one. This problem formulation is the most important step in the research. Then use MATLAB as simulation tool to identify the idea and generate the results from the simulation.

Finally, analyze the results derived in previous step. With knowledge from literature review and the simulation results from step two, explain the results and derive the conclusion of the research.

3.2 Link Capacity Calculation

In project, the link capacity is calculated by:

\[ R = \log_2(1 + \text{SINR}) = \log_2\left(1 + \frac{P_{\text{signal}}}{P_{\text{interference}} + P_{\text{noise}}}\right), \]

where \( P_{\text{signal}} \) is the power of a certain signal of the target link:

\[ P_{\text{signal}} = \frac{T_x G_t G_r}{L_p}, \]

where \( T_x \) is the power of the transmitter, \( L_p \) is the path loss that depends on the propagation model, \( G_t \) and \( G_r \) are antenna gain for transmitter and receiver respectively.

For multi-users network, a crucial factor that affects the performance of target link is the interference power from interfered link. \( P_{\text{interference}} \) denotes the sum of the interference power in the network system, which includes the interference signal from both device and base station. Both \( G_t, G_r, L_p \), and \( P_{\text{interference}} \) will be introduced in the following parts. Finally, \( P_{\text{noise}} \) is the power of the background noise that derived
from the formula given by [9]:

\[ P_{\text{noise}|dB} = 10\log(K_B T_e B) + F_N, \]

where the noise density \( K_B T_e = -174dBm/Hz \), and \( F_N \) is noise figure of the receiver, which in both communication schemes equals to 6dB. \( B \) is the available frequency bandwidth for communication, which is related with the value of noise power and throughput. For D2D communication, the bandwidth depends on the hardware device and specific channel used in transmission.

However, in conventional communication, there has a different view. Compared with traditional communication, 60 GHz mm Wave has 7GHz available frequency band, which is much higher than the traditional 5 GHz transmission. To utilize these 7G Hz bandwidth more effectively, in this project, the channel conditions adapted with Cedric Dehos’s study [16], FDD scheme is simply used to separate the 7 GHz available frequency band into four parts, each parts take part in one direction, meanwhile. In each direction, assign 64 channels to make sure different links can be transmitted simultaneously, which means the available frequency bandwidth for each channel in conventional communication is 27.3 MHz. Meanwhile, the transmission path for conventional link including the uplink and downlink, the scheduling method needs to be well designed to derive the maximum system throughput. In this project, full duplex scheme is adapted for conventional communication. The performance of the target conventional link relies on the minimum value of the throughput of uplink and downlink, which can be presented by

\[ R = \min(R_{\text{uplink}}, R_{\text{downlink}}). \]

The system throughput can be calculated in experiments through these three steps:

- First of all, we derive the system throughput without interference \( Thr_{\text{ini}} \). Once all communication nodes are paired, in spite of the effects of interference, we derive the throughput of each link assigned with D2D and conventional communication respectively. After comparing the throughput under two schemes, the one providing better performance is chosen for the corresponding pair as the initialization. When all links determine the communication scheme, using indicator \( \text{flag}_{\text{initial}} \) to record it, the system throughput without interference is derived by using formula

\[ Thr_{\text{ini}} = (Thr_1 + Thr_2 + Thr_3 + \ldots + Thr_n). \]

- Secondly, we take the interference into account. According to \( \text{flag}_{\text{initial}} \) calculated in last step, assign specific scheme for each link. Then, calculate the throughput with interference under specific scheme. For each link, comparing the performance with two schemes, and then reset the scheme according to the comparison results (use \( \text{flag}_{\text{withIF}} \) indicates). The difference between \( \text{flag}_{\text{withIF}} \) and \( \text{flag}_{\text{initial}} \) indicates the impact of interference. Finally, with \( \text{flag}_{\text{withIF}} \), calculate the system throughput with interference:

\[ Thr_{\text{withIF}} = (Thr_1 + Thr_2 + Thr_3 + \ldots + Thr_n). \]
• Finally, an accuracy improvement algorithm is purposed to guarantee the calculation of system throughput is correct. The detailed description about this algorithm is shown in Section 3.4.

3.3 Model design

3.3.1 Antenna Gain

In this project, highly directional antennas are exploited to overcome the sever path loss. Without loss of generality, the radiation pattern of directional antennas consists of both mainlobe and sidelobe(s), which is shown in Figure 3.1.

![General antenna model with mainlobe and sidelobe(s).](image)

For mobile devices, to adapt 60 GHz mmWave to D2D communications, an advanced antenna technology on small, low cost, and highly integrated transceiver products is required. Nowadays, the antenna gains on small devices can achieve 17 ± 1 dB [14], in this project, to detect the relation between antenna beamwidth and link throughput, the antenna gain is derived from the research on [15] (Adapt formula shown above) instead of using the 17 dB with the newest technology, finally, the antenna gains at mainlobe and sidelobe(s) can be respectively modeled as

\[ G_{\text{mainlobe}} = \eta \frac{2\pi}{\theta} \]  
\[ G_{\text{sidelobe}} = (1 - \eta) \frac{2\pi}{2\pi - \theta}. \]

\( \eta \) is antenna radiation efficiency which belongs to (0,1], and \( \theta \) is antenna beamwidth. Particularly, when \( \eta \) equals to 1, the antenna tends to be an ideal one, whose radiation gains from the sidelobe(s) is 0. The effect of antenna radiation efficiency will be
discussed in Chapter IV.

As for the base station, the antenna gains increase significantly with 60 GHz mmWave, since MIMO antenna arrays and a large number of directional elements can be integrated to achieve full direction coverage [13]. Figure 3.2 shows a possible steerable antenna arrays to achieve high directivity, each element in the array can have its specific directivity, which means the base station in the cell can provide high transmitting antenna gain, and receive signals from different directions.

![Figure 3.2: Steerable antenna arrays with high directivity](image)

Meanwhile, the sidelobe(s) from other links may increase the interference to target. Under this circumstance, it is necessary to discover the extent of the influence on sidelobe(s) of general antenna, i.e., antenna radiation efficiency.

### 3.3.2 Environment and Path loss Model

Adapted different parameters for LOS and NLOS path by considering different propagation conditions are necessary to derive accurate results. The main difference in two propagation conditions reflects on the average path loss and shadowing effect. This is mainly because NLOS paths may combine millimeter-wave channels. These channels require equalization and have greater propagation latency, higher power consumption, and lower data rates than LOS channels [20]. With different propagation conditions, the path loss exponent $\alpha$ is different. From paper [17] [18], $\alpha$ is chosen in LOS and NLOS as:

$$\alpha_{LOS} = 2.21, \alpha_{NLOS} = 3.18,$$
Use $p_r$ indicates the probability of LOS propagation happens. Finally the path loss is described by:

$$L_p = p_rL_{LOS} + (1 - p_r)L_{NLOS}.$$  

As $p_r$ increases in propagation environment, the effect of NLOS decreases. In this project, both D2D communication and conventional communication are considering this LOS and NLOS effects.

**(a). Conventional Communication**

An empirical and extensive model of the path loss for mmWave communication proposed by P.F.M. Smulders and L.M. Correia [7]:

$$L_p = 32.4 + 10a \log(d) + 30a(f) + 20\log(f) + (\lambda_r + \lambda_o)d,$$

$\alpha$ is average path loss exponent depends on the propagation condition. $\lambda_o$ is the specific attenuation due to the oxygen absorption, which is described with:

$$\lambda_0 = \begin{cases} 
15.10 - 0.104(f - 60)^{3.26} & 60 \leq f \leq 63 \\
11.35 + (f - 60)^{2.25} - 5.53(f - 63)^{1.27} & 63 \leq f \leq 66 
\end{cases}.$$

Where $f$ is carrier frequency, this specific attenuation can take a highly values at 60 GHz around (around 60 GHz), but it decreases by an order of magnitude when the frequency is 66 GHz. In the paper, the value of carrier frequency equals to 61 GHz.

As for $\lambda_r$, it is specific attenuation of rain and given by:

$$\lambda_r = k(f)R^a(f),$$

where $k(f)$ and $a(f)$ is:

$$k(f) = 10^{1.203\log(f) - 2.290},$$  

$$a(f) = 1.703 - 0.493\log(f).$$

However, since the effects on precipitation are not focused in the paper, the rainfall rate $R$ assumed to 0 mm/h, which means no specific attenuation due to the rain, this assumption results in the path loss model changes to:

$$L_p = 32.4 + 10a \log(d) + 30a(f) + 20\log(f) + (15.10 - 0.104(f - 60)^{3.26})d,$$
(b). D2D communication

D2D path loss model with 60 GHz is given by [19] [7]:

\[ L_p = 20\log\left(\frac{A_{d_0}}{\lambda}\right) + 10a\log\left(\frac{d}{d_0}\right) + X_{shadow}. \]

Where \( d_0 \) (5m) is the free-space reference distance, \( a \) is the average path loss exponent, \( \lambda \) is the wavelength, \( X_{shadow} \) is the parameter of shadowing effect, follows log normal distribution, with mean 0 and standard deviation \( \sigma \).

However, according to the Fernando’s study [7], the main difference of path loss model between 60 GHz and 40 GHz is caused by oxygen attenuation. The attenuation caused by rain is not that obviously. Meanwhile, since the shadow effect is not obvious in 60 GHz mm Wave transmission, the shadow effect is ignored in the paper. Finally, the general path loss model should be

\[ L_p = 20\log\left(\frac{A_{d_0}}{\lambda}\right) + 10a\log\left(\frac{d}{d_0}\right) + (15.10 - 0.104(f - 60)^{3.26})d. \]

3.3.3 Interference

According to different types of interference introduced in Chapter 2.4, interference models for each pair may have different interference sources and propagation conditions, which can be divided into four categories:

- D2D pair interferes D2D pair;
- Conventional pair interferes D2D pair;
- D2D pair interferes Conventional pair;
- Conventional pair interferes Conventional pair;

The motivation of evaluating the interference in the system is due to the fact that, for highly directional antennas, although the probability of interference generated by mainlobe beams is low, however, the interference cannot be neglected once it appears.

(a) Interference calculation

Like four kinds of interference model depicted in Figure 2.3. The calculation of interference from all links in the system to the target link \( p \) should follow these steps:

- Step1: Check whether the interference occurs between link \( (q) \) and link \( (p) \) \( (q < N_{\text{links}} \text{ and } q \neq p) \);
- Step2: If interference occurs, calculate the distance between the interfered transmitter and target receiver \( d_{t_f}(p, q) \);
- Step3: According to corresponding communication scheme of interfered link, choose the propagation model and derive the path loss \( L_{p_{t_f}}(p, q) \) and the power of interference \( P_{t_f}(p, q) \).
Step 4: Repeat step 1-3 until all links in the system are tested, get the sum of the interference from link\((q)\) and derive the interference occurred on link\((p)\).

\[
P_{IF}(p) = \sum_{q=1}^{N_{links}} P_{IF}(p, q).
\]

Specific flow chart of interference calculation is shown in Figure 3.3.

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**Figure 3.3:** The flowchart of interference calculation.

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**(b) Criteria for the interference occurred**

**Ideal Antenna**

Considering the case of ideal antennas, the sidelobe(s) is not considered, and the signal is transmitted only from its mainlobe. For instance, we consider two links \(\{T_{x1}, R_{x1}\}\) and \(\{T_{x2}, R_{x2}\}\), which are shown in Figure 3.4. Through the coordinate information of transmitters and receivers, we can judge whether there has interference between these two communication pairs. Treating \(\{T_{x1}, R_{x1}\}\) pair as the target communication pair, \(\{T_{x2}, R_{x2}\}\) pair acts as the possible interfering link. The presence of interference needs two conditions satisfied:

- **Condition 1:** \(T_{x2}\) is in the radiation range of \(R_{x1}\);
- **Condition 2**: \( R_{x_1} \) is in the radiation range of \( T_{x_2} \):

If and only if the transmitter from possible interfered link and the receiver from the target link are in the radiation range of each other, we can say there has interference generated from link2 to link1.

According to coordinates of each device, the intersection angle \( \theta_1, \theta_2 \) and \( \alpha \) (\( \alpha \) is half of antenna beamwidth) are derived to estimate whether the target point \( T_{x_2} \) is in the range of transmitter \( R_{x_1} \). If and only if \( \theta_1 < \alpha \) and \( \theta_2 < \alpha \), the transmitter of link2 will generate interference to the receiver of link1, otherwise, link2 has no effects on target communication pair \( \{ T_{x_1}, R_{x_1} \} \). Detailed description is shown below by formula.

With the coordinates of four devices: \( T_{x_1}(x, y), R_{x_1}(x, y), T_{x_2}(x, y), R_{x_2}(x, y) \), the vector of \( T_{x_2}R_{x_1} \) and \( T_{x_1}R_{x_1} \) are respectively expressed as:

\[
\overrightarrow{T_{x_2}R_{x_1}} = [T_{x_2}(x) - R_{x_1}(x), T_{x_2}(x) - R_{x_1}(x)],
\]

\[
\overrightarrow{T_{x_1}R_{x_1}} = [T_{x_1}(x) - R_{x_1}(x), T_{x_1}(x) - R_{x_1}(x)].
\]

The value of \( \theta_1 \) can be derived through these two vectors,

\[
\theta_1 = \arccos\left(\frac{\overrightarrow{T_{x_2}R_{x_1}} \cdot \overrightarrow{T_{x_1}R_{x_1}}}{|\overrightarrow{T_{x_2}R_{x_1}}||\overrightarrow{T_{x_1}R_{x_1}}|}\right).
\]

Compare the value of \( \alpha \) and \( \theta_1 \), assume \( flag_1 \) to judge whether these two links conform to condition1. Then use the same method to derive \( flag_2 \) to judge whether these two links conform to condition2. Finally, according \( flag_1 \) and \( flag_2 \), estimate whether the interference is generated from link2 to link1.

**General Antenna**

As for general antenna, the biggest difference is the effect of sidelobe(s). Due to the existence of sidelobe(s), interference model is different compared with ideal antenna situation. Figure 3.5 depicts these four interference patterns when sidelobe(s) of antenna cannot be neglected. The criteria of these four interference patterns depend on...
the intersection angle $2\theta$ and antenna beamwidth $2\alpha$. The definition and criteria of these four interferences patterns are summarized as follows:

- **Pattern 1**: Mainlobe of interfered transmitter points to mainlobe of target receiver. When $\theta_1 < \alpha$ and $\theta_2 < \alpha$, both $R_{x1}$ and $T_{x2}$ are in the radiation range of each other, this pattern can be simplified as interference model adapted in ideal antenna, since only mainlobe generates interference to mainlobe, there is no interference of sidelobe(s) for this pattern.
- **Pattern 2**: Mainlobe of interfered transmitter points to sidelobe(s) of target receiver. When $\theta_1 < \alpha$ and $\theta_2 > \alpha$, $T_{x2}$ is in the radiation range of $R_{x1}$, but $R_{x1}$ is not in the radiation range of $T_{x2}$.
- **Pattern 3**: Sidelobe(s) of interfered transmitter points to mainlobe of target receiver. When $\theta_1 > \alpha$ and $\theta_2 > \alpha$, $T_{x2}$ is not in the radiation range of $R_{x1}$, but $R_{x1}$ is in the radiation range of $T_{x2}$.
- **Pattern 4**: Sidelobe(s) of interfered transmitter points to sidelobe(s) of target receiver. When $\theta_1 > \alpha$ and $\theta_2 > \alpha$, both $R_{x1}$ and $T_{x2}$ are not in the radiation range of each other.

Comparing the value of $\theta$ and $\alpha$, the type of interference generated by link2 can be determined and calculated for link capacity.
(c) Interference analysis algorithm

Since the ideal antenna is one special case of the general directional antenna model, in next section, the interference calculation of general antenna will be introduced in detail. Figure 3.6 is derived to show how general antenna generates interference in the system. The difference among interference patterns introduced in last section is that the sidelobe(s) of antenna for base station (BS) are neglected since BS is a large-scale device compare with the mobile devices. For BS, it is easy to centralize the power of signal in its mainlobe, which makes us not to consider the influence of sidelobe(s) on BS, i.e., the antenna for BS is considered as ideal antenna. This decision makes Situation (b) and Situation (d) in Figure 3.6 is different with D2D connections as interfered link.

![Figure 3.6: D2D pair generates interference to another D2D pair.](image)

To calculate interference in multi-users system, each communication pair should be
considered whether there has interference with another pair one by one which causes numerous calculation. In real life, the central controller does not have enough time and resource to calculate this much, which means the system should not only focus on the accuracy of the performance, but also consider complexity of calculation as an important factor in interference analysis algorithm.

Fortunately, according to the Figure 2.3, an assumption can be easily derived that conventional pair generates interference is a small probability event since the location of mm Wave BS at the edge of the cell. In other words, the main interference in our system is D2D pair interferes D2D pair. In the project, the difference of system with DID model and the system with AI model will be considered respectively. The result is shown in Chapter IV to verify whether the interference of D2D pair interferes D2D pair is main interference.

3.4 Accuracy Improvement Algorithm

Since the interference analysis highly depends on the communication scheme for each communication pair. It is necessary to choose scheme correctly. Accuracy improvement algorithm is purposed to improve the accuracy of the value of system performance, through iterations

Through the description in Section 3.2, we know that the schemes of some links may change after considering interference. Under this circumstance, before we switch the scheme for this specific link, we need to consider the influence on other pairs since the interference model from other links may change. To avoid this problem, the iteration based accuracy improvement algorithm is purposed in system.
The core of accuracy improvement algorithm is repeating the calculation when the performance is enhanced by switching the communication scheme. Figure 3.7 shows how to derive the system throughput in one iteration. Since the performance may change after considering the interference in the system, switch $f_{algwithIF}(p)$ one by one. In each pair, recalculate the system performance after switching the scheme into another one (D2D or Conventional). If the performance is worse than before, then switching the communication scheme back, otherwise remains the change of scheme and continue to the next pair. After checking schemes of all pairs, derive the system performance with current communication scheme group $flag_{reverse}$.

Compare the performance of $Thr_{reverse}(1)$ and $Thr_{withIF}$ if the capacity of system decreases, there is no need to continue the next iteration, the results of $Thr_{withIF}$ is the optimal system throughput. Otherwise, the throughput for this iteration $Thr_{reverse}(1)$ is the optimal results until now. However, considering the interference pattern may change after some schemes change, the next iteration is necessary. Repeat the iteration process until the performance is poor than the previous iteration result and eventually get the maximum system performance with optimal assignments decision for communication schemes (Use $flag_{final}$ indicates).

Figure 3.8 shows the steps of accuracy improvement algorithm in details. The $n$th iteration indicates the algorithm cannot improve performance anymore. Finally, the value of $Thr_{iteration}(n - 1)$ is the maximum system throughput.
Figure 3.8: Flow chart of accuracy improvement algorithm.
Chapter IV: Results Analysis

To consider a realistic scenario of a conventional mobile network, the parameters from a general urban conventional system shown in Table 2. The values are based on [17] [18] and [19].

Table 4.1: Applied parameters for Conventional and D2D communication.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>D2D communication</th>
<th>Conventional Communication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Radius (m)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Carrier Frequency (GHz)</td>
<td>61</td>
<td>61</td>
</tr>
<tr>
<td>Transmit Power (dBm)</td>
<td>20</td>
<td>46</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>800</td>
<td>27.3</td>
</tr>
<tr>
<td>Noise Density (dBm/Hz)</td>
<td>-174</td>
<td>-174</td>
</tr>
<tr>
<td>Noise Figure (dB)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Path loss exponent $\alpha$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOS</td>
<td>2.21</td>
<td>2.21</td>
</tr>
<tr>
<td>NLOS</td>
<td>3.18</td>
<td>3.18</td>
</tr>
<tr>
<td>Antenna radiation efficiency for general antenna $\eta$</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Antenna radiation efficiency for ideal antenna $\eta$</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

4.1 Results for Single Link System

4.1.1 The effect on the LOS coefficient $p_r$

Based on the description in Section 2.3, the simulation is created and run. By repeating the simulation 10000 times, we find the probability that the performance of D2D is better than the conventional highly depends on $p_r$, which is the coefficient of the probability of the path condition is LOS. The system is under ideal antenna with 10 degrees antenna beamwidth. Table 4.2 shows the relation between $p_r$ and the probability that the performance of D2D is better than conventional communication.

Through the Table 4.2, we can see that the probability that D2D link performance is better increases as $p_r$ increases. Even with the worst condition which is $p_r =0.1$, there are still 23 percent links get a better performance by using D2D links. This phenomenon encourages us to use two communication schemes simultaneously, and the performance of the system can be improved at least 20 percentages. The results show that it is necessary to study on implementing the D2D scheme and conventional communication working simultaneously in the network, especially for 60 GHz
mmWave since it is suitable for small area communication.

Table 4.2: The relation between \( p_r \) and the probability that the performance of D2D is better than conventional communication.

<table>
<thead>
<tr>
<th>( p_r )</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.2412</td>
<td>0.2396</td>
<td>0.2282</td>
<td>0.2344</td>
<td>0.2349</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2639</td>
<td>0.2474</td>
<td>0.2442</td>
<td>0.2485</td>
<td>0.2511</td>
</tr>
<tr>
<td>0.3</td>
<td>0.2636</td>
<td>0.2659</td>
<td>0.2621</td>
<td>0.2604</td>
<td>0.2683</td>
</tr>
<tr>
<td>0.4</td>
<td>0.2716</td>
<td>0.2779</td>
<td>0.2713</td>
<td>0.2788</td>
<td>0.2740</td>
</tr>
<tr>
<td>0.5</td>
<td>0.2920</td>
<td>0.2898</td>
<td>0.2927</td>
<td>0.2925</td>
<td>0.3053</td>
</tr>
<tr>
<td>0.6</td>
<td>0.3096</td>
<td>0.3116</td>
<td>0.3163</td>
<td>0.3174</td>
<td>0.3081</td>
</tr>
<tr>
<td>0.7</td>
<td>0.3298</td>
<td>0.3341</td>
<td>0.3538</td>
<td>0.3334</td>
<td>0.3409</td>
</tr>
<tr>
<td>0.8</td>
<td>0.3796</td>
<td>0.3714</td>
<td>0.3653</td>
<td>0.3760</td>
<td>0.3716</td>
</tr>
<tr>
<td>0.9</td>
<td>0.4509</td>
<td>0.4357</td>
<td>0.4428</td>
<td>0.4395</td>
<td>0.4480</td>
</tr>
<tr>
<td>1.0</td>
<td>0.6196</td>
<td>0.6247</td>
<td>0.6279</td>
<td>0.6226</td>
<td>0.6340</td>
</tr>
</tbody>
</table>

### 4.1.2 The relations between distance and system throughput

Since the throughput of communication link highly depends on the path loss during propagation, in this project, the path loss depends on the distance. To derive the performance of system with 60 GHz mmWave, the relation between distances and throughput, in both communication schemes, is researched in this project.

On the one hand, according to the path loss model of D2D communication, path loss only depends on distance, meanwhile, since the path loss has a reverse ratio with the throughput, an obviously conclusion is derived that the performance of a D2D communication pair decreases as the distance between two devices increases. On the other hand, the performance of conventional link not only relies on the distance of uplink and downlink communication, but also depends on the scheduling scheme. However, since the full duplex scheduling scheme is fixed to achieve the maximum throughput in conventional communication, the throughput is simply depends on two distances. While the uplink distance or downlink distance decreases, the throughput will increase either, however, there is no monotonous relation between pure uplink distance or downlink distance and the system throughput.

In this project, 60 GHz mmWave technology is adapted in the project which is also prefer short distance transmission, under this circumstance, it is easily to get an idea that use D2D communication with 60 GHz mmWave can efficiently improve the system performance.
4.1.3 Comparison of the performance of two communication schemes

As a result, the CDF plot of the throughput with the pure conventional link and D2D link can be derived (Shown in Figure 4.1) to get a deeper understanding on the performance of two communication schemes with 60 GHz mmWave.

![CDF plot of throughput](image)

Figure 4.1: The comparison of the performance of two communication schemes

The intersection point shown on Figure 4.1 corresponding to x axis at throughput of 640 Mbps, divides the plot into two parts, which means 53% of D2D links and conventional links can achieve this data rate. At left side, which we can call it as low rate part, the conventional connection is better than the D2D communication in low rate. Among these experiments, due to D2D communication is highly relative with the distance between two users, and there are six mmWave base stations in the cell, conventional link has a better resistance even two users are randomly generated in the cell, which means the conventional communication has a more stable performance. From Figure 4.1, we can find nearly 49% of D2D communication among simulations cannot achieve the data rate to 500 Mbps, as for conventional communication, conventional links in all simulations achieve this data rate. So in a word, from left side, which is for low data rate communication, conventional communication is better than D2D communication.
However, on the right side, the results totally reverse, the D2D links can achieve higher data rate, even more than 3G bps, which means in the system that requires higher data rate, D2D communication has significantly advantages compared with conventional communication.

Ultimately, 60 GHz with pure conventional communication can achieve 640 Mbps with antenna arrays and approximately conditions, compared with 5 GHz transmission, the network throughput with conventional communication can only achieve 54M bps [21], which means the 60 GHz mmWave can improve the performance nearly 13 times. This improvement encourages us to research the application of 60 GHz mmWave. Meanwhile, determine the suitable communication scheme under specific occasions is also a good way to improve the performance. For example, for system with low data rate requirement, conventional communication is a suitable scheme to achieve data rate in a more stable status, however, D2D communication is a useful tool to achieve higher data rate requirement. In a word, system with 60 GHz mmWave adapting D2D and conventional communication working simultaneously is a possible way to improve the system performance.

4.2 Results for Multi-Users System

A multi-users system is researched in this scenario, all experiments repeat in 500 times to derive convincing results. The same values of parameters adapted in single link network used in the system (Like Table 4.1 shown). The interference situation bases on two models: DID model and AI model, which is introduced previously. Meanwhile, the value used to compare among CDF plots is derived from the average system throughput of each simulation.

In this scenario, the results will be introduced by these four sections:
- Derive the impact of antenna radiation efficiency;
- Quantized analysis on the ratio of D2D communication adapted in network;
- Analysis on the effects of antenna beamwidth with ideal antenna and general antenna;
- Analysis on the effects of traffic load with ideal antenna and general antenna;

4.2.1 The impact on antenna efficiency

Antenna radiation efficiency decides the energy of mainlobe can use to transmit information. The higher antenna radiation efficiency will decrease the energy that sidelobe(s) wastes. Figure 4.2 shows the relation of network performance and antenna
radiation efficiency.

Antenna radiation efficiency ($\eta$) determines the energy that sidelobe(s) of antenna can derive. Figure 4.2 shows the relation between $\eta$ and system throughput. When $\eta$ equals with 1, the antenna is ideal antenna, compare the performance among different $\eta$. From Figure 4.2, we can derive three standpoints:

- Higher $\eta$ reduces the system throughput;
- Lower $\eta$ causes the difference of performance between DID model and AI model is more obviously.
- As the $\eta$ decreases, the impact of $\eta$ on system throughput decreases rapidly.

The formal two viewpoints can be easily explained from the definition of $\eta$. Higher $\eta$ means more energy that sidelobe(s) derive to generate interference to target link, which will cause the decrease of system throughput. This is mainly caused by the interference model chosen for the network. The difference between these two interference models can summarize to one aspect: the types of interference for AI
model is more than DID model. With ideal antenna, there is no interference generated by sidelobe(s), the interference is generated from the mainlobe of other links which mainly depends on the antenna beamwidth (the impact of antenna beamwidth will be described in detailed in next section), which makes the interference generated from two models has little difference when the antenna beamwidth is small. Higher $\eta$ causes higher interference from sidelobe(s), and then effects AI model more.

Meanwhile, standpoint three shows the impact of sidelobe(s) has a limitation in our system, since there is no sidelobe for BS antenna, if $\eta$ decrease to a threshold, the interference caused by sidelobe from device will increase to an exaggerated extent, the central controller will assign conventional scheme to links, which will stop decrease of system performance. This is the reason caused the phenomenon shown in Fig 4.4.

In our project, to demonstrate the difference of performance with ideal antenna and general antenna more clearly, $\eta$ is chosen to 0.9 in the experiments.

### 4.2.4 Ratio for D2D communication

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$N_{\text{links}}$</th>
<th>25</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Ideal</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DID</td>
<td>0.7505</td>
<td>0.7342</td>
</tr>
<tr>
<td></td>
<td>AI</td>
<td>0.7766</td>
<td>0.7394</td>
</tr>
<tr>
<td></td>
<td>General</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DID</td>
<td>0.0596</td>
<td>0.0237</td>
</tr>
<tr>
<td></td>
<td>AI</td>
<td>0.0956</td>
<td>0.1012</td>
</tr>
<tr>
<td>30</td>
<td>Ideal</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DID</td>
<td>0.3121</td>
<td>0.3063</td>
</tr>
<tr>
<td></td>
<td>AI</td>
<td>0.3370</td>
<td>0.3309</td>
</tr>
<tr>
<td></td>
<td>General</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DID</td>
<td>0.046</td>
<td>0.0158</td>
</tr>
<tr>
<td></td>
<td>AI</td>
<td>0.076</td>
<td>0.1230</td>
</tr>
</tbody>
</table>

The ratio of D2D communication ($P_{D2D}$) under different conditions is shown in Table 4.3, each result is derived from 500 simulations. From the Table 4.3, three conclusions can be derived:

- With general antenna situation, $P_{D2D}$ is incredible low;
- The interference model and traffic load has nearly no effects on $P_{D2D}$;
- $P_{D2D}$ is highly related with antenna beamwidth, especially in ideal situation.
The difference of ratio mainly depends on the interference generated from sidelobe(s), since the sidelobe(s) of base station is ignored in the project, interference generated by sidelobe(s) is mainly from D2D pair, which means the more interference from sidelobe(s), the central controller will assign more conventional scheme to communication link, which results in the current situation and proves our explanation that links prefer conventional scheme when $\eta$ is to low.

### 4.2.3 The impact on antenna beamwidth

![Figure 4.3: Performance comparison with different antenna beamwidth under a 75 links network with ideal antenna and general antenna](image)

**a) Ideal Antenna**

By using highly directional antenna arrays, the system with 60 GHz achieves higher data rates. However, small antenna beamwidth ($\theta$) means superior difficulty on coupling the antenna. To derive the effects of the antenna beamwidth with 60 GHz mmWave, results of several tests of 75 links network with different antenna
beamwidth under 500 simulations is shown in Figure 4.3.

Figure 4.3 shows system performance with different $\theta$ under different interference models. The line closer to the left, means the performance under this situation is worse. On the contrary, the line closer to right means the system has a better performance. The blue star and black diamond full lines present performance with aggregated interference (AI) model with beamwidth 10 and 30 degrees under ideal antenna respectively. Another two full lines with blue triangle and black square show the performance with DID model. As the $\theta$ increases, system throughput decreases significantly. This is because the probability of interference generated ($P_r(If)$) is different with different $\theta$. The increase of $\theta$ means the transmit power ($T_x$) and $P_r(If)$ both increase. $T_x$ and $P_r(If)$ are two factors that influence the network performance. The formal one can improve the link capacity, and the latter one determines the interference power. The result shows that with larger antenna beamwidth, the consequence caused by enhancing interference cannot be contracted by larger transmit power.

Another interesting result can also be derived through the figure. Compare the performance under different interference models with the same $\theta$, we can find when $\theta$ is small, like 10 degrees, compare with two blue lines (triangle and star full line), the system throughput with DID model and with AI model are approach. However, the plots with 30 degrees beamwidth (black square and diamond lines), the performance of system has clearly difference between two interference models, the system throughput under AI model is worse than DID model, especially compare with 10 degrees beamwidth system. The discovery shows that for different $\theta$, the influence of interference models are different. The phenomenon is mainly due to the location of mmWave BS. In our project, the BSs are at the edge of the cell, Like Figure 2.3 shown, with 10 degrees directional antenna, the interference from mainlobe occurs not so often in conventional communication. However, in D2D communication, since the devices are randomly generated in the system, $P_r(If)$ is much higher compared with conventional link, which causes the DID is main interference in the system. As for larger beamwidth situation, $P_r(If)$ is caused by rapidly increasing conventional communication, which diminishes the difference between two models. Finally, the AI model has the same performance with DID model under ideal antenna with small $\theta$, which means the interference model can only adapt DID model under small $\theta$ to decrease the complexity of interference calculation and then improve the capacity of central controller.

b) General Antenna

Compare with the performance with ideal antenna, system throughput with general antenna has same trends with previous one. As $\theta$ increases, the system throughput decreases no matter in which conditions and the performance of system with DID
model is also better than AI model. However, an interesting phenomenon with general antenna is that the effect of $\theta$ is not the biggest factor to influence the performance. For example, in Figure 4.3, red triangle and green square dash lines represent the performance of network with DID model under 10 degrees and 30 degrees respectively. The difference is not that big between these two lines. From the plots with other value of beamwidth, the same results derived, at least the difference is not as big as the ideal antenna shown (blue and black lines). On the contrary, the difference caused by interference model has more obvious influence on system throughput. Compared with red triangle, green square and green diamond dash lines, the red triangle and green square dash lines present the network that has same interference model with different $\theta$, the green square and green diamond dash lines show the network that has different interference model with same $\theta$. From these lines, we can find the difference caused by interference model is much bigger than the difference caused by different antenna beamwidth.

The reason for this situation is mainly because the interference generated in the system not only depends on the $\theta$, but also relies on the sidelobe(s) of antenna. The function of sidelobe(s) will generate new interference in the system, which means the beamwidth still effect the system performance but not as big as in the ideal antenna system. Meanwhile, with highly directional antenna, the small beamwidth is hard to generate interference, but sidelobe(s) from other links can always influence the target link, which produces the difference between different interference models. Interference generated from sidelobe(s) changes the performance of two interference models, makes the interference generated in AI model is much larger than in DID model.

c) Comparison

Figure 4.3 also shows the comparison of the performance of system with ideal antenna and general antenna together. Compared with these plots, some observations are worthy of research. First, the value of system throughput decreases rapidly by adapting general antenna. For example, compare the value of 75 links system with DID model under 10 degrees beamwidth between ideal antenna and general antenna (blue triangle full line and red triangle dash line), the range of the throughput with ideal antenna system can achieve from 1.9G bps to 3.2G bps. However, in general antenna network, it can only achieve from 0.9G bps to 1.1G bps. The performance decreases nearly 60 percent.

Then, another interesting point is that the difference of performance caused by two interference models is nearly same with ideal antenna and general antenna. With ideal antenna, as the $\theta$ equals with 10 degrees, the CDF of system throughput during 500 simulations derived from AI and DID models (blue full lines) nearly coincide with
each other, meanwhile, in general situation, the difference is almost the same between two CDF plots (red dash lines). This shows the influence of interference model on system performance remain the constant as the sidelobe(s) generate interference.

Finally, back to the effects of antenna beamwidth, we can see the influence of $\theta$ diminishes in the performance of network. Compare with plot under AI model with different antenna system. The difference between the system throughput of ideal antenna network with 10 and 30 degrees beamwidth (blue star and black diamond full lines) is nearly 1.2G bps. However, in the same conditions with general antenna (red star and green diamond dash lines), the difference decreases to only nearly 0.3G bps.

The reason for the performance of general antenna system worse than ideal antenna network is obvious. The mainly difference of ideal antenna and general antenna is antenna radiation efficiency. Sidelobe(s) generated in the general antenna caused new interference in network. Like the interference model described in Chapter 3.3, the interference generated by sidelobe(s) increase the value of interference in both AI and DID model for general antenna. In ideal antenna, $\theta$ determined whether there has interference, but for general antenna, the value of $\theta$ is only decided the interference from mainlobe or sidelobe(s). This difference causes the impact of $\theta$ in general antenna is weakened. Finally, the interference increase in the system cause the decrease of the system throughput, this is why we get the plot of Figure 4.3.

4.2.4 The impact on traffic load

With different traffic loads, the performance of network has a significantly difference. As the number of links increases in the system, the interference situation and the complexity of calculation also increase. To derive the relation between traffic load and performance, some different simulations setup in the experiment. As the number of links ($N_{\text{link}}$) increases in the network, the CDF of system performance with ideal antenna and general antenna is shown in Figure 4.4.
Figure 4.4: Compare the performance with 10 degrees antenna beamwidth under network with different number of links with ideal antenna and general antenna.

a) Ideal antenna

The right part of Figure 4.4 shows the performance of network with ideal antenna, the trends of CDF plot cannot indicate the impact of traffic load and system throughput. The most interesting appearance is some links have intersection points between networks with different traffic load. For example, for the system with AI model, compare the performance of 25 links and 75 links (blue star and red diamond full lines), the intersection point is at around 2.4G bps. Nearly 40 percent of simulations for system with 25 links and 75 links achieve this data rate. The former part shows the system with more links is better than less links, which indicates in low data rate, systems with more links can have a better performance under ideal antenna. On the contrary, the latter part shows the opposite result which means the less links system can achieve higher data rate. Compare with other lines, same conclusion can also be derived easily.
The phenomenon shows relation between $N_{\text{links}}$ and system throughput, which the system with more links has a more stable performance, when the requirement for data rate is not high, the traffic load in network can be busier, otherwise, less $N_{\text{links}}$ can provide a higher performance for system. This is mainly caused by network with more links can be distributed more uniform in the cell. The 75 links network integrates all situations that link may generate, however, 25 links cannot satisfy this requirement. It is just like the performance comparison between D2D communication and conventional communication in section 4.1.3. The 25 links network can achieve higher data rate but not stable enough just like the performance of D2D link.

Meanwhile, when $N_{\text{links}}$ is small, the performance of two lines (black diamond and blue star full lines) are similar, and the difference caused by different interference models also increase as the traffic load in the system increases, it is just like relation of small beamwidth and system throughput derived in Section 4.2.1 (a). The reason caused this phenomenon is that as the system with large number of links, the interference $P_{i}(If)$ may increase since the links are randomly generated in the system. Meanwhile, the small $N_{\text{links}}$ makes the interference hard to generate in the system, which makes the performance under DID model and AI model looks similar when $N_{\text{links}}$ equals with 25. In a word, the impact on $N_{\text{links}}$ is not as obvious as antenna beamwidth under ideal antenna.

**b) General antenna**

Figure 4.4 also shows the performance of network with different traffic load under general antenna in the left of plot. The plot shows that traffic load nearly has no effects on system throughput. The difference between networks with different traffic loads under same interference model looks really small (blue star and red diamond dash lines). Meanwhile, the intersection point between blue star and green square dash lines shows the same phenomenon with the comparison under ideal antenna.

However, networks with same interference models under different links nearly coincide in the left part and separated latter (black triangle and green square dash lines, blue star and red diamond dash lines) indicates the difference of general antenna. This phenomenon exactly shows the impact of interference generated by sidelobe(s) of antenna in system. In the network, with general antenna, the interference is determined by both the mainlobe and sidelobe(s) of antenna. As $N_{\text{links}}$ increases, the probability of interference generated by mainlobe will not has a significantly increase while the antenna beamwidth keeps the same. However, when there has one more link adds into the system, the interference generated by sidelobe(s) will definitely increase, especially from another D2D pair. In addition to the conclusion derived from last section, the network with more links has a better performance in relatively low throughput. The interference generated from sidelobe(s)
offsets this advantage and makes the plots looks coincident with each other in the former part. These two reasons makes there has no intersection point between network with 75 links and 25 links with same interference model.

c) Comparison

Figure 4.4 also compares the performance of system with ideal antenna and general antenna together on $N_{\text{links}}$. Compared with the impact of antenna beamwidth, the difference of value of $N_{\text{links}}$ didn’t change the performance so much. Meanwhile, through the figure, an easily conclusion derived that the performance of ideal antenna is much better compare with general antenna, the performance decrease nearly 60 percent by adapting general antenna, which means interference generated by sidelobe(s) has significantly influence on the performance.

Meanwhile, we can find the range that the network can achieve becomes really small, the 75 links network with AI model under ideal antenna can achieve from 1.9G bps to 3.2G bps (red diamond full line), but with same conditions, the general antenna can only get 0.9G bps to 1.2G bps. This means the interference caused from sidelobe(s) by D2D pairs is really large in general antenna, to maintain the performance, the central controller will assign the conventional scheme to the link. Combine the data in Table 4.3, we can find the ratio of D2D scheme decreases significantly under the general antenna, which cause. In a word, the less links in system can achieve higher data rate, but more links can help the performance remain in a stable range, according to different environment conditions, the most suitable value of $N_{\text{links}}$ should be chosen.

Finally, the intersection points on plot show that the relation between $N_{\text{links}}$ and system throughput is not monotonous, the choice of $N_{\text{links}}$ should be considered the requirements of system.
Chapter V: Conclusion

The project demonstrates the behavior of the performance of system combining D2D and conventional communication simultaneously with 60 GHz mmWave. Based on the defined objective, the project investigates into the four questions to derive the conclusion results. During our attempt to find the characteristic of 60 GHz mmWave, the traffic load, antenna beamwidth, LOS coefficient and some other factors researched in the project. Depending on interference analysis and accuracy improvement algorithm, the performance of system combining two communication schemes derived in the project. Through this project, we can derive these conclusions. First, the performance of network with 60 GHz mmWave with pure conventional communication improves 17 times compare with 5 GHz transmissions. Next, with D2D communication, the network performance can achieve at least 20 percent improvement compared with pure conventional network. Then, traffic load and antenna beamwidth are highly related with system performance, choose suitable parameters under different conditions, the network can derive best performance. Finally, the impact of interference cannot be neglected even highly directional antenna adapted, but the interference analysis shows that DID interference model is enough for the system with 60 GHz, especially in for highly directional antenna with proper conditions, like small antenna beamwidth. This discovery provides an efficient method to save process time of assigning communication schemes for links from central controller.

In a word, through the research of the project, the performance of network can be improved significantly with D2D and conventional communication working simultaneously in 60 GHz mmWave under appropriate parameters and conditions.
Chapter VI: Future Work

Subsequently to this research project, further studies can be done to evaluate the benefit of performance of the system with 60 GHz mmWave. Deeper and more accurate models can be designed would be interesting as well.

To improve the system performance, a dual band operation by combining 5 GHz and 60 GHz mmWave simultaneously can not only improve system on the resistibility of extremely terrible propagation environment, but also contribute to promote the application of 60 GHz mmWave. After all, 5 GHz communication is still one of mainstreams in communication area. This dual band operation can be implemented in our system in the future.

Meanwhile, it is worth noting that although the accuracy improvement algorithm did not improve the performance in simulations, the performance of system throughput not only depends on the factors investigated in the project, some other factors like number beams for base station antenna and shadow effect are not considering in this paper, these conditions may affect the performance, which needs our accuracy improvement algorithm to ensure the results are correct. In the future, we can find the accuracy improvement algorithm can improve the performance of system in which parameter or condition.
Reference:


[20]. Rappaport, T.S. ; Ben-Dor, E. ; Murdock, J.N. ; Yijun Qiao, “38 GHz and 60
