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毫米波蜂巢式通訊系統干擾協調與資源分配

Multi-Cell Interference Coordination under mm-wave Cellular Systems

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國立臺灣大學（碩）博士學位論文
口試委員會審定書

毫米波蜂巢式通訊系統干擾協調與資源分配
Multi-Cell Interference Coordination under 5G mm-wave Cellular System

本論文係陳駿彥君（R02942032）在國立臺灣大學電信工程學研究所完成之碩（博）士學位論文，於民國 104 年 07 月 21 日承下列考試委員審查通過及口試及格，特此證明

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摘要

基於近幾年新的量測結果和大量可用頻帶，毫米波做為未來第五代移動通訊系統的趨勢已越發明顯。目前大部分對於毫米波的研究都還處於新通道的模型化，以及如何在移動中提高連接穩定性的階段，媒體接取層的研究甚少。本篇論文主要著墨於毫米波蜂巢式系統下，媒體接取層如何處理不同基地台間會存在的干擾。毫米波的基地台由於指向性很強，可以利用這個特性達到更高的空間及頻率重複使用效果。但也由於指向性的特性，會對鄰近特定用戶造成一定干擾，而此種干擾性質又與 LTE 很不同。因此我們提出了一個可以讓鄰近基地台做某種程度的合作，來達到消除干擾又同時保持空間重複使用的效果。

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Abstract

Based on the recent measurement results in NYU (New York University), people start to reconsider the possibility of using mmWave as the 5G cellular system. The intriguing huge available bandwidth in mmWave frequency also contribute this trend. Most research in mmWave cellular field focus on the antenna beamforming and the beam tracking stability due to the directional characteristic. Few people are studying mac layer design or the interference problem, which they think should be a minor problem compare to LTE. This article will focus on the mac layer design that can deal with the inter-cell interference at the same time. Due to the directional feature, spatial reuse and frequency reuse can be improved. However, this feature also leads to strong signal at specific direction which can cause interference, which would be rather different from that of LTE. We proposed a mechanism that can allow some cooperation between adjacent cells. In this way, we are able to eliminate interference and at the same time preserve the high spatial reuse feature of mmWave signal.

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Chapter 1

Introduction

1.1 Background

Traffic demands for cellular communication systems has been growing at a stunning rate. Future application might require beyond 4G or 5G cellular systems to support multi-gigabits per second (Gbps) peak throughputs and tens of megabits per second (Mbps) at cell edge. According to address this problem, recently the millimeter-wave (mm-wave) bands has drawn much attention, and people start to explore the possibility of building next generation cellular system upon these unutilized bands. mm-wave refers to the frequencies that the wavelength is shorter than 1cm, which is around 30GHz to 300GHz, and its most attractable feature is the huge available spectrum. Recent years the development from 2G, 3G to 4G system quickly consumed much of the lower frequency bands (under 6GHz), ISM bands are also occupied by many different technologies such as blue-tooth and wi-fi. Spectrums below 6 GHz are mostly used or discontinuous, making it hard to leverage capacity by just increase the bandwidth in a communication system. On the other hand, mm-wave bands can easily offer up to several giga-hertz (GHz). The mm-wave band

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position compared to other technologies is in Figure 1.1. Figure 1.2 shows the possible mm-wave available spectrum according to the signal absorption by O_2/H_2O, dotted circle area can be promising bands.

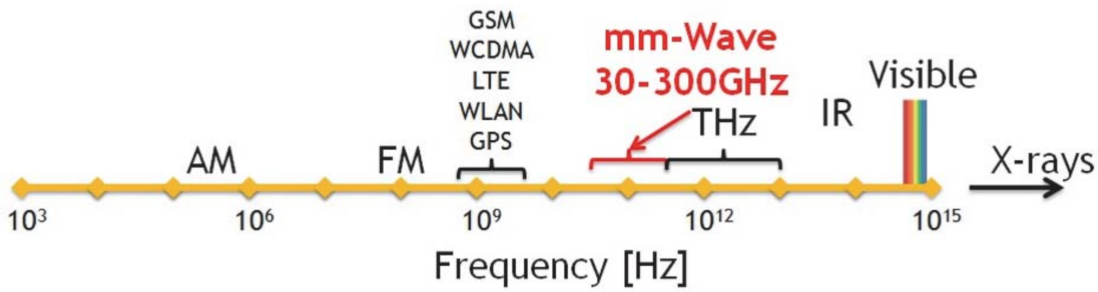

Figure 1.1: Relative Location of mm-wave band [1]

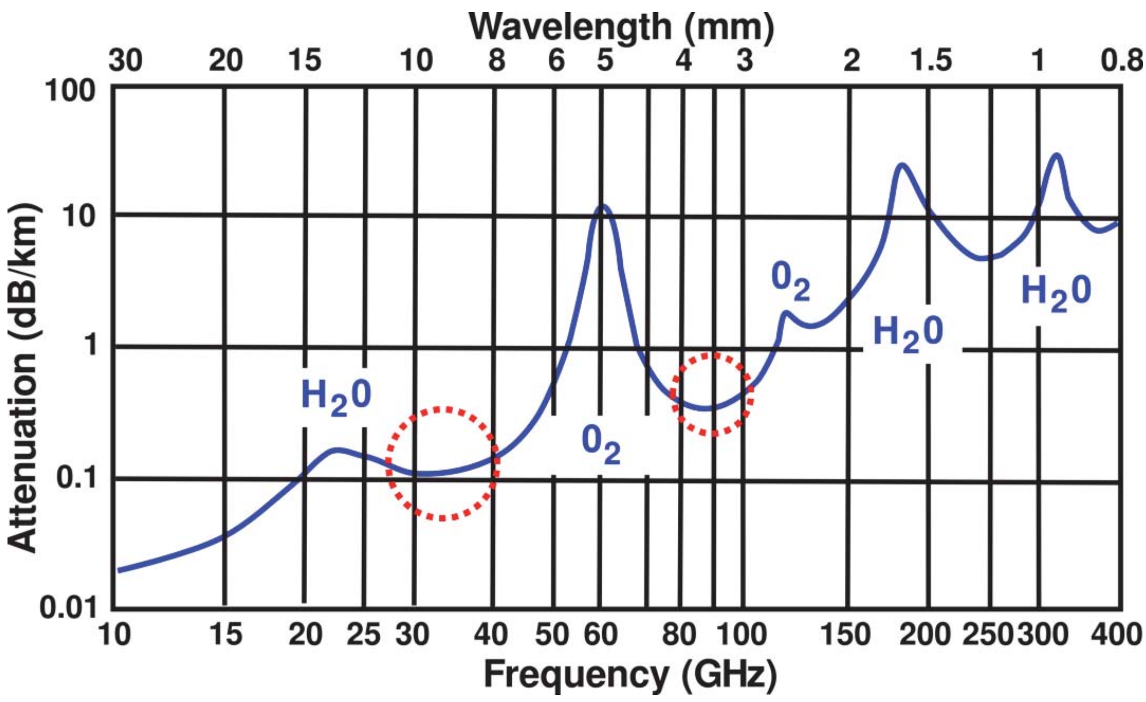

Figure 1.2: Possible Promising mm-wave band [2]

The reason why mm-wave was not considered as the main frequency for cellular system, lies in the general concept that signals in higher frequencies tend to degrade much faster according to the Friis transmission equation. The free-space path loss in 28GHz is around 20dB higher than 2.5GHz for example. Actually there are existing military usage in the mm-wave area, but in order to compensate the large path loss, large array of an-

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tennas are used, which is unlikely to be implemented on the current mobile equipment or base station. However, since now we are limited by the scarce spectrum in traditional frequencies, researchers start to work on the mm-wave area. Figure 1 illustrates the possible mm-wave region that could be used for future system.

Everything must have a beginning. A team in New York University (NYU) led by Professor Rappaport unveiled the mysterious mm-wave characteristics and its feasibility on supporting the next generation communication system [4][5][6]. In NYU's work, large amount of measurement is performed and the results are convincing. This is why more and more people start to throw themselves into various related research area. The mature cost-effective CMOS technology that can operate in the mm-wave region also makes a promising statement. With all above knowledge, it is not hard to imagine that people put anticipation on mm-wave band.

As a new band of communication, physical characteristics of mm-wave should first be examined carefully. NYU did a series of measurements in order to discover the features [7][8]. Most of the parameters they measured can be used to fit in present channel models of lower bands, which means they currently try to use old channel models to apply for mm-wave. Some new concepts are also proposed such as ``Block Probability", ``Outage Probability" etc. Although whether old channel models can be apply to mm-wave is a issue, we in our work adopt the old channel models and replace values with NYU's results.

1.2 Contribution

Many papers state that the signal of mm-wave is noise-limited. Noise-limited means only noise does the major damage to the receiving signal. This deduction is reasonable, since signals are more vulnerable to obstructions and might degrade severely at the cell edge.

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Although by beamforming we largely enhance the power of a signal, the beam formed is should narrower when compared to signals transmitted by previous generations systems. Narrower beams means the probability of collision should be very small theoretically. All of these leads to the conclusion of noise-limited feature.

However, we wonder how high the probability of collision is when multiple beams are used at the same time. Also, a base station is usually partitioned into several sectors/cells. The cells in the same site might as well have an effect of interference due to the angle distribution measurement results revealed by NYU. In our initial simulation, indeed the inter-cell interference still have some effect on the throughput loss, which is different from the noise-limited imagination. Discovering these inter-cell interferences and the possible management scheme is our first contribution. Another contribution is that we developed a scheduling method for utilizing spatial domain resources.

The following chapters are organized as follows. In chapter 2 some related work is presented, including several different phases of our problem. Chapter 3 is the system model of our mm-wave scenario. For chapter 4 the detailed description lying on the system model in chapter 3 is discussed. The main scheme we proposed is showed in chapter 5, and after that simulator structure and simulation results are stated in chapter 6,7 respectively. Finally chapter 8 is the conclusion.

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Chapter 2

Related Work

Our work touch two different areas, ``spatial domain resource allocation" and ``interference management". Related works in each of these areas are presented in this chapter.

2.1 Spatial domain Resource Allocation

Spatial domain resource allocation is alike the problem under MU-MIMO scenario, but usually MU-MIMO does not handle large numbers of antennas up to 64 for example. With smaller number of elements, the beams shaped by them are not narrow beams but can be imagined as a random shape, since their weights are intended to do nulling according to channel matrix. Although we adopt code-book based beamforming rather than zero-forcing or other techniques, the user-selection algorithms in MU-MIMO can still be referenced. A famous user-selection method called ``Semi-Orthogonal User Selection for MU-MIMO" uses channel coefficient relations between UEs as an influential index [9]. We use some of the orthogonality concept of this method to develop our algorithm.

Apart from the tunable weights of antenna elements in MU-MIMO, under the category of ``Directional Antenna" some MAC layer design also have been discussed. Here we list

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some of them. There are many papers discussing about the MAC issues of directional wireless network scenario, but most of them are under the 802.15.3c or 802.11ad environment, and are all ad-hoc situation[10--15]. The main difference is that 802.11ad or 802.15.3c scenarios mainly handles numerous point-to-point connections while cellular BS will have to allocate many number of UEs at the same time. An overview of directional antenna and its mac layer issues are well described in [12], but also mainly relate to ad-hoc situation. In [13][14], the 802.11ad AP acts as a coordinator and group non-interfering transmissions. For WPAN [11] introduced a concept of *Exclusive Region* to define the concurrent transmission region. Cellular BS can deal with interferences between transmissions with more information, as a result, the solution should be quite different.

There is a work that is similar to our work [16]. It considers 60GHz LOS signals and discuss time-spatial domain resource allocation. In this work (PWBU Heuristic Allocation) some heuristic metrics is considered and we use it as the baseline for comparison. For convenience we call it **ChangYu** in the following chapters.

2.2 Cross Cell Interference Management

In LTE, Inter-Cell Interference Coordination (ICIC) has several solutions. For example, the category **Static ICIC** has two kind of methods, one is ``Reuse 3" which allocate completely different bands for the 3 sectors that comprise a site. The other is called ``Soft Reuse", where each sector can have higher power on one of the three different bands. However, these coordination is based on the physical characteristic of lower frequency. In lower band, the signals transmitted are assumed that they can affect the whole sector. However, narrow beams in mm-wave band can greatly reduce the interference situation which we conventionally want to deal with. Moreover, the source of interference could

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be distinct too. As a result, we believe the interference coordination might be dissimilar to the ordinary solutions. We will show some of our observation in the following chapters to justify these ideas.

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Chapter 3

System Model

This chapter we briefly illustrate our system model including the mm-wave scenario we consider, the cellular system structure we adopt and the assumption on antennas. The final section illustrates our basic MAC layer settings.

3.1 Usage Scenario

We consider an outdoor urban downlink scenario served by mm-wave base stations, which will operate at 28GHz. Each of the multiple base stations may serve multiple users using beamforming technique, and with the advantage of the narrow beam width, large spatial multiplexing gain could be explored. This scenario is shown in Figure 3.1. The spatial multiplexing gain is similar to the gain achieved by MU-MIMO but with possibly more independent channel conditions for the users. When spatial dimension is used for multiplexing, there is a certain probability that signals between cells may still interfere with each other. Although under beamforming and such narrow beamwidth, the likelihood may decrease dramatically but once the beams formed by different cells collide, the interference might be very strong and can not be underestimated.

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In Figure 3.2 we show the possible interference situation when the mm-wave bands and narrow beamforming is used at the same time. As we can see in cell1, the beam that serves ue1 may interfere with signal transmitting to ue2 when the beam power is strong enough (through the dotted arrow). On the other hand, the beam serving ue4 may interfere with the signal transmitting to ue3 from cell2. We believe that there should be some coordination between closely placed cells so that this kind of interference can be prevented. Hopefully through these coordination, cells that are placed densely can achieve higher gain.

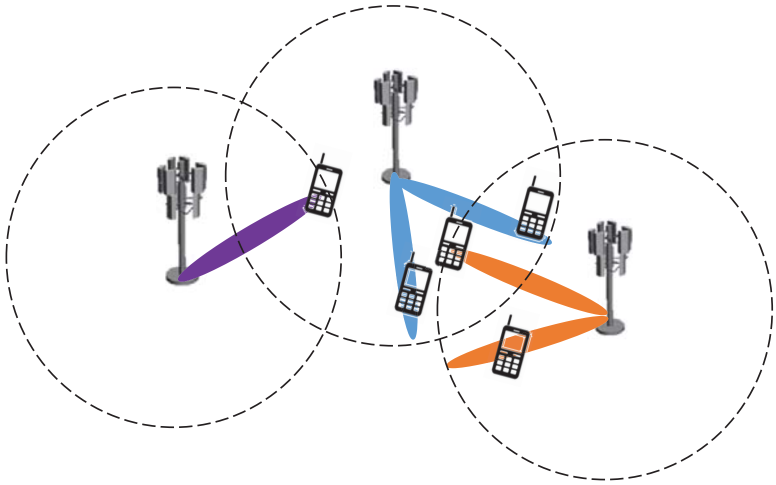

Figure 3.1: Multiple base stations utilizing spatial dimension gain in downlink scenario

3.2 Cellular System

Due to the signal feature of higher frequency, we assume in the future the base stations that operates in the mm-wave band will be deployed with high density. In order to align with the conventional cellular deployment method, we decided to deploy the cells and sites same as the topology specified for IMT-advanced [17]. Figure 3.3 well illustrates the cellular deployment we adopt and basically is the same as LTE. The only difference would be the inter-site distance, which will be tuned smaller in our simulation. Three cells comprise a site, and many sites comprise the whole cellular system, and each cell

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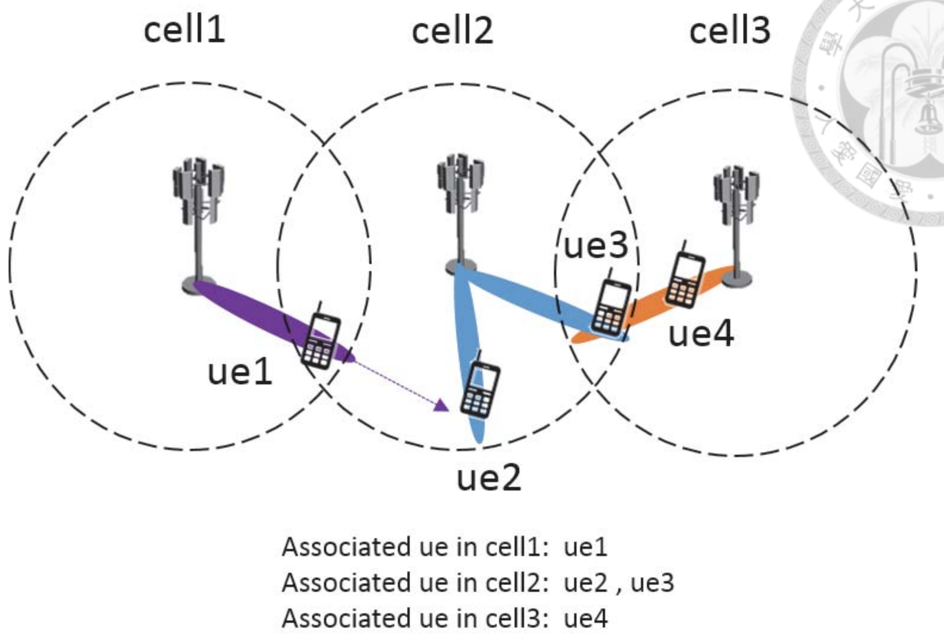

Figure 3.2: Interference situation

is equipped with independent antenna system. During the article we may use ``cell'' and ``sector'' interchangeably.

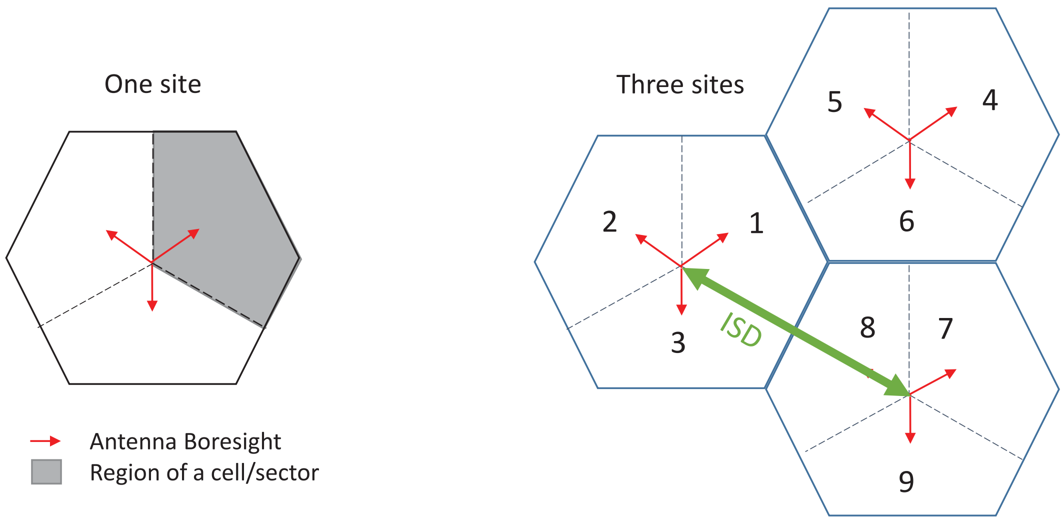

Figure 3.3: mm-wave Cellular System

On the left side is a site composed of three cells/sectors. The arrows specify the direction that the antenna of that sector is facing to (boresight). On the right side is the whole architecture with three sites, the numbers represent cell ID.

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3.3 Antenna Assumption

Although there might be a high chance that both base station and UE side will use beamforming technology when operating in the mm-wave region, for simplicity in our work we assume beamforming only applies at the cell side. Cell side has an antenna array with eight elements, while the gain pattern of these elements have asymmetric gain over all directions and the gain pattern is referenced from [3](Figure 3.4), with HPBW 65°. UE side has only one antenna element and its pattern is omni-directional (same gain over all directions). The weights of the eight antenna elements at the cell side can be adjusted in order to achieve beamforming.

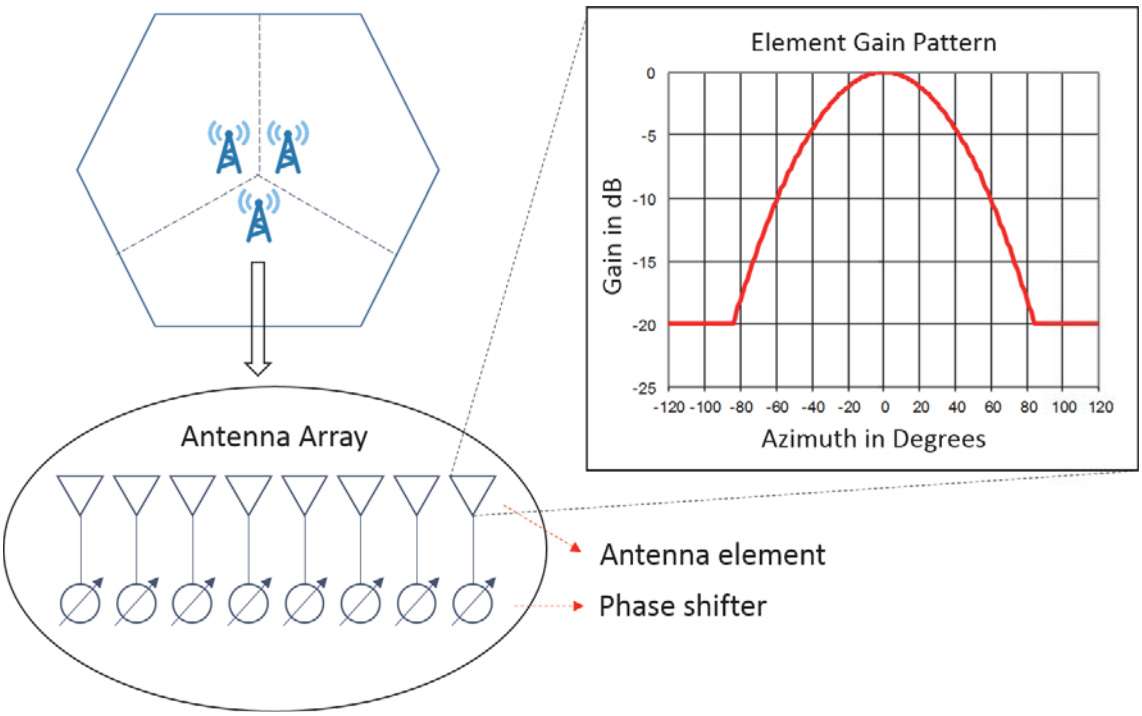

Figure 3.4: Cell Antenna Elements

Our beamforming is code-book based and has only eight sets of weight for each element, each correspond to a direction in a cell and all the directions split the whole 120° sector (Figure 3.5), 90° is the antenna boresight. Unequal magnitude gain in Figure 3.5 is due to the gain pattern of each elements, which has less gain when the direction gets

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farther away from the antenna boresight.

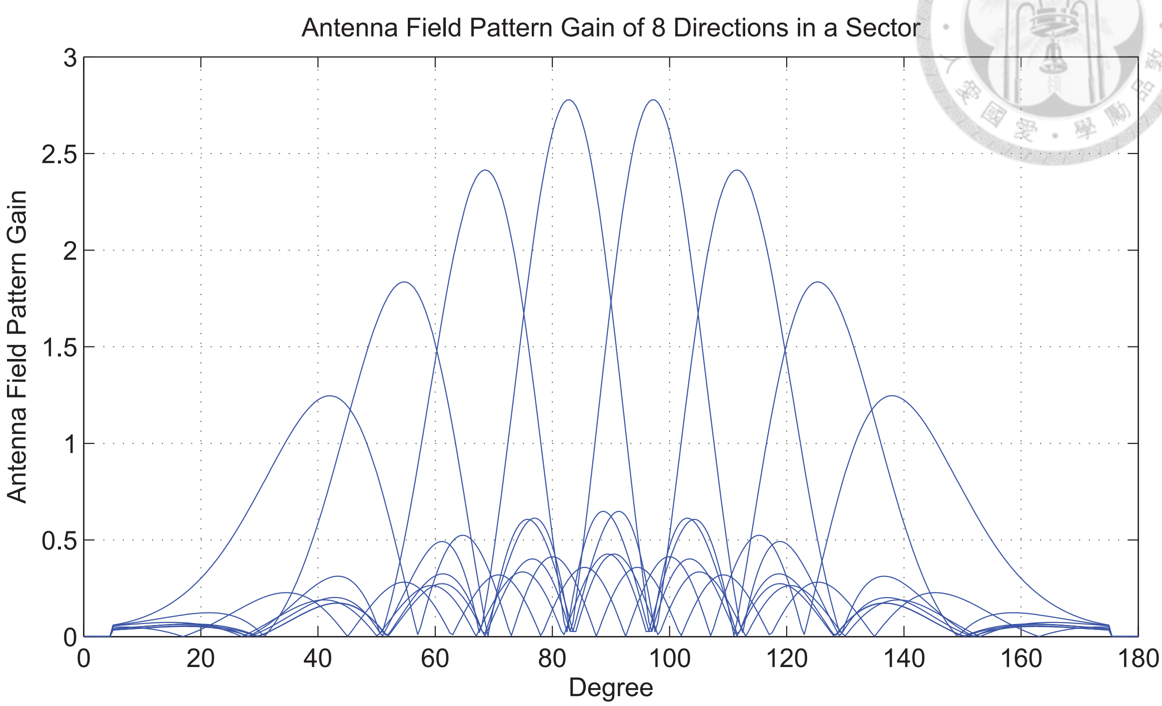

Figure 3.5: Beamforming Directions and Field Pattern Gain

We also assume our cell is capable of simultaneous beamforming and can serve multiple UEs at the same time similar to MU-MIMO situation, at the cost of power reduction. This situation is showed in Figure 3.6. In other words, we assume multiple RF chain at the cell side and they can combine multiple sets of code-books with multiple data stream for UEs to achieve simultaneous beamforming. Realistic results of the combination of two code-books is showed in Figure 3.7. The solid line is the two code-books where we intend to beamform to 67.5° and 97.5° respectively. The dotted line represents the one code-book that combines the two directions after normalization management. It is obvious that the combined two beams have smaller field pattern gain, which leads to about half power gain at each direction.

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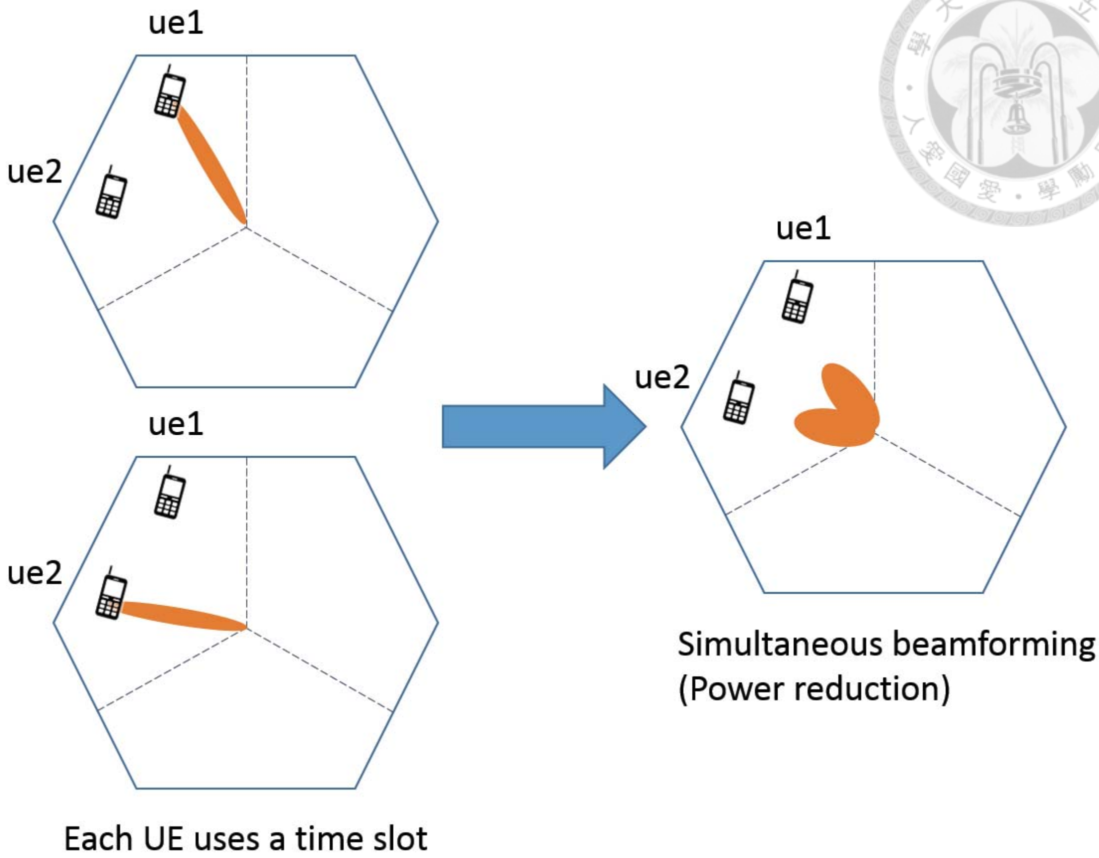

Figure 3.6: Simultaneous Beamforming

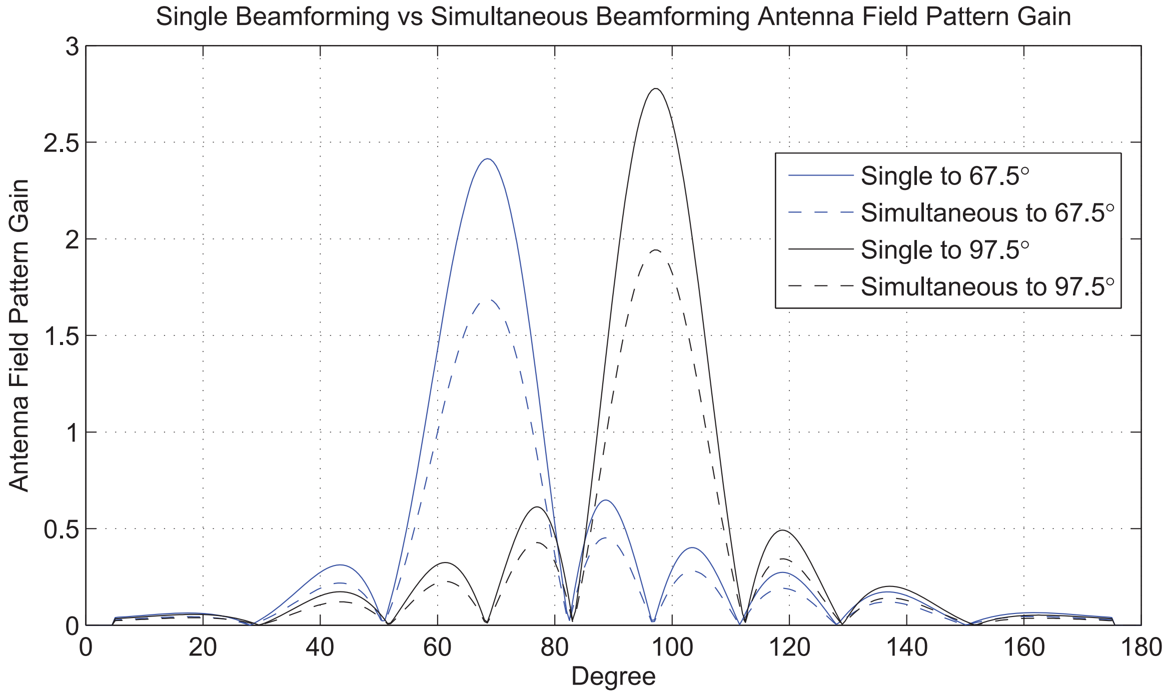

Figure 3.7: Single vs Simultaneous Beamforming Antenna Field Pattern Gain

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3.4 Other Assumptions

The characteristic of mm-wave band is its large bandwidth. Concerning we must use beamforming to form narrow beams as to serve UEs, we assume in our system there is no frequency division. When a UE is scheduled in a time slot, it has the resource of the whole bandwidth (1GHz in our system). A UE is moved to the end of queue once scheduled, and the scheduling ends when the specified frame number is reached. A UE only uses the best beam for its data transmission, which is the beam that it can receive the most power from. The traffic is set to full buffer state. As for throughput estimation, we adopt shannon capacity formula.

The usage scenario is discussed in section 3.1. Here we note another important concepts. Since outdoor urban is our scenario, we adopt the measurement results presented in [7] but with the **NLOS** part only due to less information on the **LOS** part. In [7], the Angle of Departure (AoD) and Angle of Arrival (AoA) have uniform distribution over all the directions for the **NLOS** situation. This feature results in possible intra-site interference as illustrated in Figure 3.8. In our system only **NLOS** signal is considered.

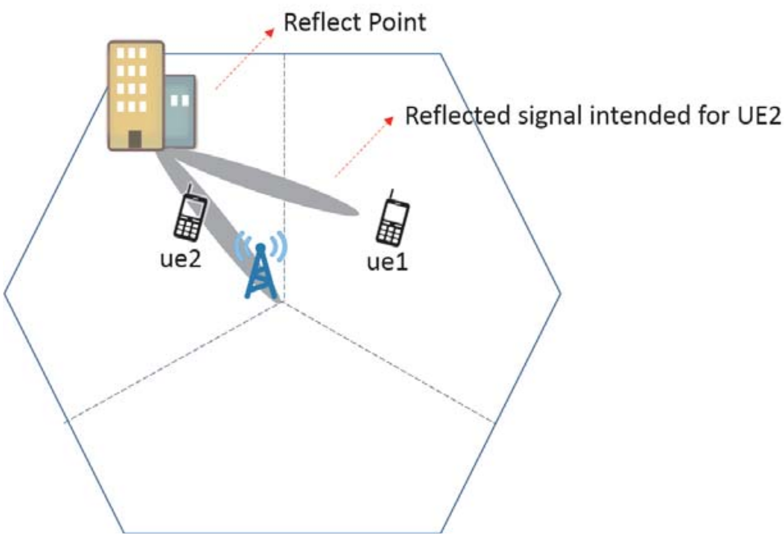

Figure 3.8: Intra-site Interference

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Chapter 4

Problem Definition

Under the system model stated in the previous chapter, in this chapter we define more details of the problem we want to solve. Some observations will be presented in the first section, and in the second section we denote the features we have found in those observations and further deduce the boundary and definition of our research problem.

4.1 Observation

We want to examine the intensity of the kind of interference we mentioned in section 3.1. Two scenario is simulated.

- TDMA
- MU-Beamforming

The first one is the interference when a cell only serves a UE at each time slot, we call it TDMA. The second is the interference when a cell is enabled to use simultaneous beamforming, we call it MU-Beamforming (Multiple User Beamforming) and these two terms would be used interchangeably. Recall in chapter 3, antenna array at the cell side is

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assumed to have the ability to perform beamforming and an alternative what we define as simultaneous beamforming. This simultaneous beamforming is somewhat alike MU-MIMO but the weights of the antenna elements are pre-decided for each codebook and cannot be tuned to achieve certain MIMO gain like zero-forcing for example.

For simultaneous beamforming, we now just use a preliminary algorithm, which avoids UEs that are highly correlated in terms of the best beams they use. For each of the two scenario, three lines are drawn for three conditions. Listed below are the interferences that is considered under these three different conditions.

- Condition1: Intra-cell interference
- Condition2: Intra-site interference(other cells in the same site) + Intra-cell interference
- Condition3: Inter-site interference(cells in other sites) + Intra-site interference + Intra-cell interference

Figure 4.1 shows the three conditions, and the simulation results are in Figure 4.2. Here we use three sites for our system as depicted in Figure 3.3, ISD is the variable parameter. Details of the simulator is in Chapter 6. It can be seen from Figure 4.2, when ISD gets smaller, intra-site interferences would start to make a difference (the gap between condition1 & 2). On the other hand, the effect of inter-site interferences have the same trend but is less severe.

4.2 Research Problem

In this section we properly define the research problem based on our observation in section 4.1. Due to the fact that intra-site interferences damage the throughput more, we focus on

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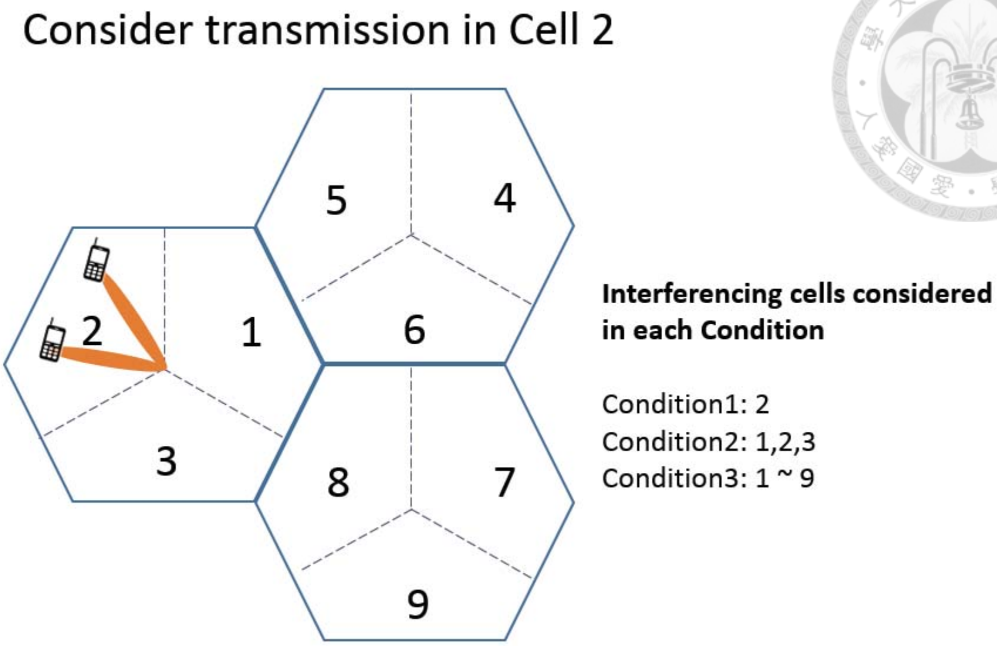

Figure 4.1: Interferences for the three conditions

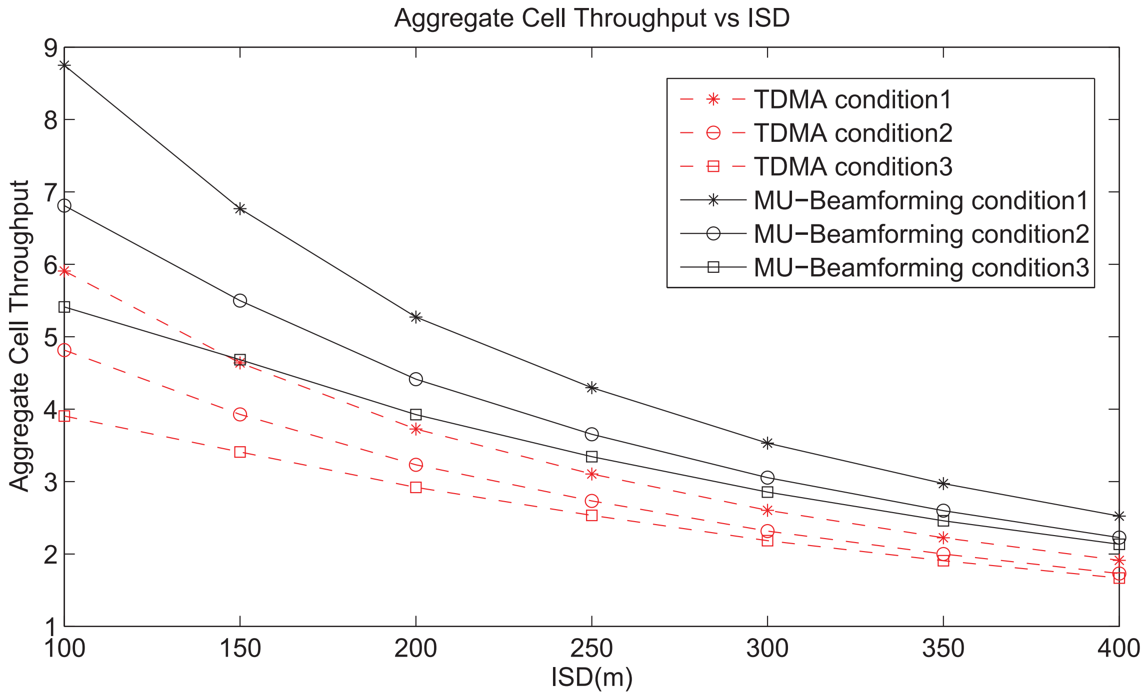

Figure 4.2: Aggregate Cell Throughput Under Different Conditions

intra-site interference management, which is also a multiple cell management except that cells are at the same site.

Under the basic assumptions in chapter 3, we want to find a management procedure be-

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tween cells in the same site that can in some degree eliminate the beam collision. Whether it is TDMA or MU-Beamforming, our method should both work well on these two scenarios. We also seek to find an efficient time-spatial domain resource allocation within a cell to be the basic algorithm when interference is considered. Figure 4.3 briefly summarize the research problem.

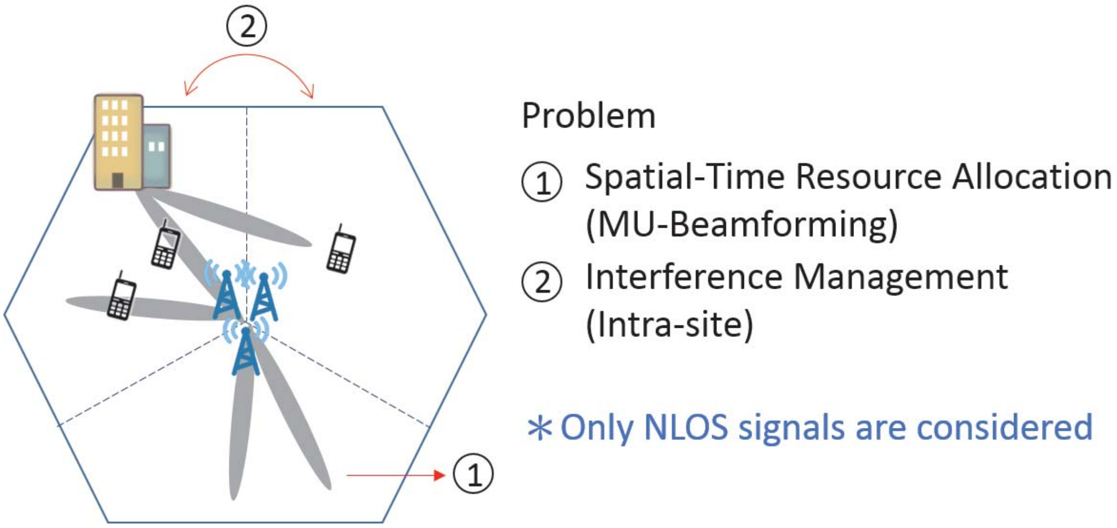

Figure 4.3: Problem Scenario

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Chapter 5

Proposed Scheme

In this chapter we introduce our proposed scheme. As mentioned earlier, our scheme seek to solve the interferences caused by adjacent cells in the same site. The first section will describe our baseline for comparison, the second section describe basic interference management procedure used in TDMA scenario, and the third section describe both on the resource allocation method for MU-Beamforming and the interference management.

5.1 Baseline

For the baseline, we need a scheme that does not have any coordination between cells and at the same time has a nice throughput performance. The scheduling of each cell should be independent. We use a greedy algorithm as the baseline, which means we add UEs into a time slot whenever the aggregate throughput increases. Algorithm 1 is the greedy algorithm implemented in each timeslot. Apart from Algorithm 1, a previous work on spatial resource allocation under mm-wave band is also used for one of our baseline. In this article we call it **ChangYu** for convenience, the detail of this method will not be shown [16].

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Algorithm 1: Greedy Algorithm for cell resource allocation

Input: queue
Output: ScheduledUE, queue
Th = 0;
$ScheduledUE$ = an empty array;
for $j = 1; j \leq Length(queue);$ **do**
  UE_j = $queue(j)$;
  th = Aggregate throughput when UE_j is put into this time slot;
  if $th > Th$ **then**
    Add UE_j into $ScheduledUE$;
    $Th = th$;
  end
end
move UEs in $ScheduledUE$ to $queue$ end;
return $ScheduledUE$, $queue$;

5.2 Scheme for TDMA

As mentioned in chapter 3, each UE is served by the best beam & cell combination. In TDMA scenario, because in each time slot only one UE is served in a cell, so the chance of beam collision is low. But still, there should be some gain when interference management is applied. We want beam selections in each cell be dependent and avoid beams that could damage already scheduled UEs. In order to achieve coordination, we assume the three cells take turns in the scheduling period so that one cell can examine what beams and UEs have been scheduled by other cells. The lead cell may change according to subframe index as to take care of fairness among cells.

The selection of UEs and beams are restricted by a certain interference threshold. In Figure 5.1 we depict how we eliminate some beam choices, we name our scheme for TDMA ``**Intra-site Aware TDMA**". The order of scheduling in the figure is cell1 then cell2 then cell3. UE2 and UE3 will check whether the beam used to serve UE1 may damage their throughput by some degree and will not be scheduled if the reduction is severe. The threshold is set at the situation that the scheduled UE will not have a degrade

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of throughput more than 20 percent. In this way, a cell will have some beam choices being blocked because the UEs scheduled in previous cells might be damaged by these beam choices in the current cell. However for high SNR users, the 20 percent rule might eliminate nearly all the beam choices, so we set a maximum of 20dB gap.

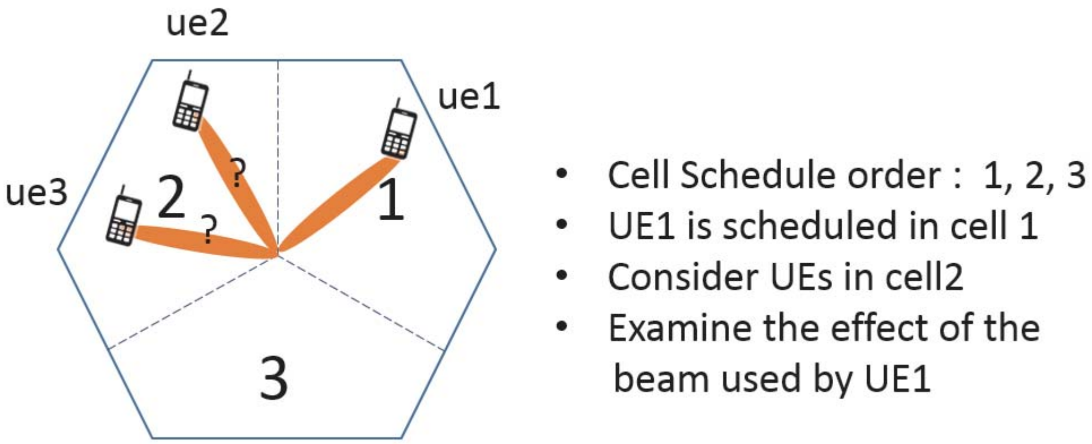

Figure 5.1: **Intra-site Aware TDMA**

5.3 Scheme for Simultaneous Beamforming

Scheme for simultaneous beamforming are divided into two parts. Multi-cell coordination subsection describe a method that is alike the cell coordination for TDMA but with less constraints. Intra-cell Resource Allocation subsection discuss how well the spatial domain resource can be utilized.

5.3.1 Intra-Cell Resource Allocation

Since we limit the UEs to use only limited beam direction choices, the main resource allocation problem is equal to find the best combination of UEs in each time slot, which we can call it a user selection problem. User selection has been discussed in MU-MIMO area and one famous heuristic is a semi-orthogonal method [9]. In this method they first

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calculate the orthogonality between the already selected users and the candidate users. After that they pick the most orthogonal users until the orthogonality decrease to a certain level. Here we adopt a similar idea but in a reverse mode.

In our system the scheduling will not stop when all user is scheduled once and users may go back in queue to wait for another transmission. So instead of picking the most orthogonal user, we pick users that has orthogonality over a certain threshold. In this way, fairness can also be taken care of. Now the question becomes how well can we set the threshold to utilize spatial dimension gain.

First we try to find a way to define the orthogonality in our system. Channel response H is used in [9], but because we are using pre-decided directions, we decide to use the final received power from these beams as an intuitive index. For example if userA can receive 68dBm power from beam1 and use it as the serving beam, while it receives 75dBm for beam2, then we can say that beam2 is withn 10dB from the serving beam and might be a potential threat beam selection for userA. If we set the orthogonal threshold to be larger than 10dB, then beam2 is blocked in this time slot. In order to find the proper threshold we calculated the distribution of this orthogonality index in Figure 5.2.

Figure 5.3 presents another important aspect. For different SNR region, the effect of interference is not the same. For low SNR users, the main throughput loss is ruled by SNR. Figure 5.3 illustrates the orthogonality threshold for each SNR. The percentage means the throughput loss ratio if a beam within an strength is used simultaneously with the current user. Combining the results in Figure 5.2 and 5.3, we decide to set the threshold to be the same as the 20% line in Figure 5.3 but with a maximum of 10dB. How the parameters is set will discussed in the next subsection. The algorithm of our intra-cell resource allocation is called **Basic Orthogonal Channel-Based Method** (Algorithm 3).

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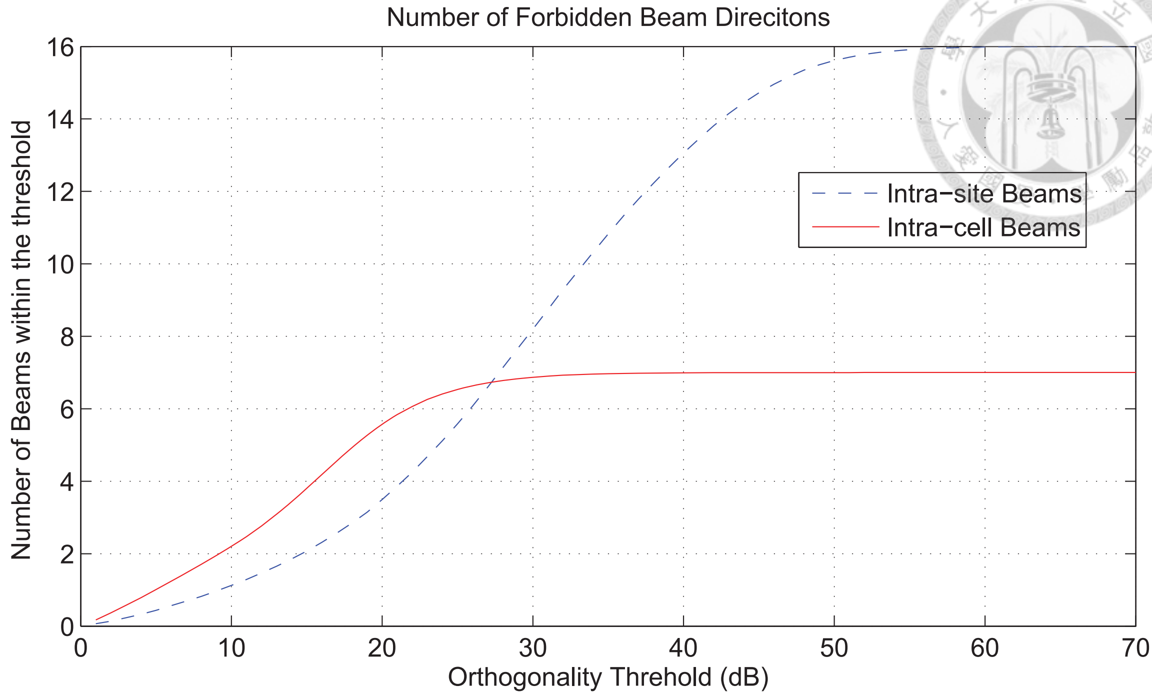

Figure 5.2: Beam Distribution

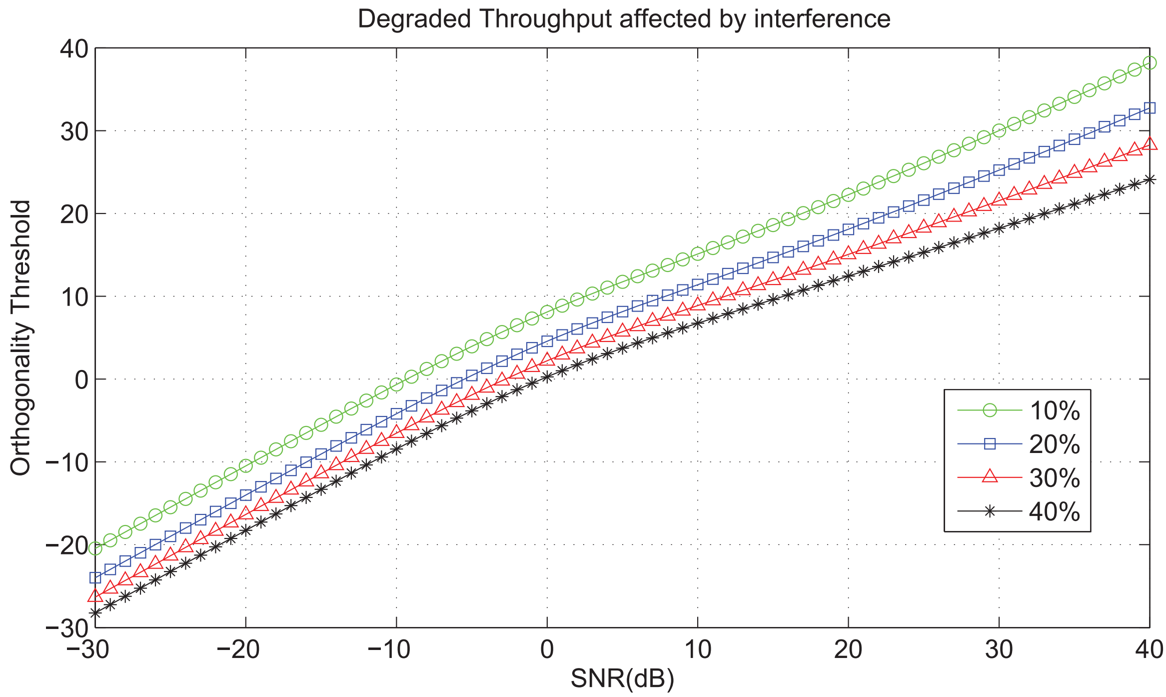

Figure 5.3: Threshold observation

Inside algorithm 3 there is a function called **CheckSimultaneousThroughput**, which is used to guarantee the throughput for low SNR users. Low SNR users is dominated by noise and the promise of orthogonality of other beams will not benefit them much. In order

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to take care of these users, the decision of whether they should be transmitted with other UEs must be specified by another rule. We compare the throughput when they can be the only UE in the time slot (the same in TDMA) with the situation of transmitting along with other UEs. Because TDMA means expectedly the frequency of UE being scheduled is lower than using MU-Beamforming, the we compare the throughput of TDMA divided by 2 with the throughput of transmitting along with other UEs. This is by expecting that other UEs will follow the same selecting rule when the same situation is encountered.

5.3.2 Multi-Cell Coordination

Originally each cell is an independent scheduling unit. However, now we assume there is some coordination between these cells in the same site during scheduling time. We want some coordination but at the same time does not harm the fairness among these cells. The scheme is basically the same as in TDMA, cells take turns in scheduling period and previous cells' choices is considered. However now in each cell more beam directions are used and the probability of beam collision raises. The maximum threshold of 20dB no longer works in the MU-Beamforming scenario because it would erase all the beam choices. Instead, we lower the threshold to 10dB according to the distribution diagram in Figure 5.2. We assume in each time slot, the number of simultaneously scheduled user in each cell will not defer much, so that this orthogonality threshold can still be used as a measurement.

The threshold setting comes from a quick calculation. We want the cell's to coordinate but without harming their choices of UEs.At 10dB in Figure 5.2, intra-site beam is 1, which means when the third cell is scheduling, the previous 2 cells might have forbidden 4 directions (assume 2 UEs in a time slot). If the 20% line also reaches 10dB(SNR =

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10dB), the third cell has just enough choices to have also 2 UEs in the time slot. This threshold can prevent cells from being affected too much and lost the original possible throughput gain.

Algorithm 3 presents the method of purely considering intra-cell interference. The combination with **Multi-Cell Coordination** is presented in Algorithm 4. The combined algorithm is called **Intra-site Aware Orthogonal Channel-Based Method**. The difference lies in the consideration of other cell's scheduling results. The two new variables added into Algorithm 4, **OtherCellUE** and **OtherCellBeam**, are other cell's previous selections and are taken into account.

Algorithm 2: CheckSimultaneousThroughput

Input: UE,ScheduledUE
Output: simul
th_TDMA = throughput when only UE is scheduled in the time slot;
th_simul = throughput when UE is scheduled along with UEs in ScheduledUE;
if $th\_simul > th\_TDMA/2$ **then**
    simul = true;
else
    simul = false;
end
return *simul*

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Algorithm 3: Basic Orthogonal Channel-Based Method

Input: queue
Output: ScheduledUE, queue

$ScheduledUE$ = an empty array;
$ScheduledBeam$ = an empty array;
for $j = 1; j \leq Length(queue)$; **do**
  UE_j = $queue(j)$;
  $beam_j$ = Beam index used by UE_j;
  $available$ = true;
  /* Check if UE_j is affected by previous beam selections */
  foreach $beam_p$ **in** $ScheduledBeam$ **do**
    $interference$ = power received by UE_j from $beam_p$;
    $signal$ = power received by UE_j from $beam_j$;
    $threshold$ = 20% throughput degrade threshold of $signal$;
    if $signal - interference <$ *min(threshold,10)* **then**
      $available$ = false;
    end
  end
  /* Check if $beam_j$ affects previous selected UEs */
  foreach UE_p **in** $ScheduledUE$ **do**
    $interference$ = power received by UE_p from $beam_j$;
    $signal$ = power received by UE_p from its own beam;
    $threshold$ = 20% throughput degrade threshold of $signal$;
    if $signal - interference <$ *min(threshold,10)* **then**
      $available$ = false;
    end
  end
  /* Check if UE_j should not transmit with other UEs */
  simul = **CheckSimultaneousThroughput**(UE_j,$ScheduledUE$);
  if $available == true$ **and** $simul == true$ **then**
    Add UE_j into $ScheduledUE$;
    Add $beam_j$ into $ScheduledBeam$;
  end
end
Move UEs in $ScheduledUE$ to $queue$ end;
return $ScheduledUE$, $queue$;

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Algorithm 4: Intra-site Aware Orthogonal Channel-Based Method

Input: queue
Output: ScheduledUE, queue
$OtherCellUE$: UEs scheduled by other cells;
$OtherCellBeam$: Beams selected by other cells;
$ScheduledUE$ = an empty array;
$ScheduledBeam$ = an empty array;
for $j = 1; j \leq Length(queue);$ **do**
    UE_j = $queue(j)$;
    $beam_j$ = Beam index used by UE_j;
    $available$ = true;
    /* Check if UE_j is affected by previous beam selections */
    foreach $beam_p$ **in** $ScheduledBeam$ **and** $OtherCellBeam$ **do**
        $interference$ = power received by UE_j from $beam_p$;
        $signal$ = power received by UE_j from $beam_j$;
        $threshold$ = 20% throughput degrade threshold of $signal$;
        if $signal - interference <$ *min(threshold,10)* **then**
            $available$ = false;
        end
    end
    /* Check if $beam_j$ affects previous selected UEs */
    foreach UE_p **in** $ScheduledUE$ **and** $OtherCellUE$ **do**
        $interference$ = power received by UE_p from $beam_j$;
        $signal$ = power received by UE_p from its own beam;
        $threshold$ = 20% throughput degrade threshold of $signal$;
        if $signal - interference <$ *min(threshold,10)* **then**
            $available$ = false;
        end
    end
    /* Check if UE_j should not transmit with other UEs */
    simul = **CheckSimultaneousThroughput**(UE_j,$ScheduledUE$);
    if $available == true$ **and** $simul == true$ **then**
        Add UE_j into $ScheduledUE$;
        Add $beam_j$ into $ScheduledBeam$;
    end
end
Move UEs in $ScheduledUE$ to $queue$ end;
return $ScheduledUE$, $queue$;

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Chapter 6

Simulator

This chapter we first go briefly go through our simulation procedure. Then in the second section Channel Model generation is illustrated, because mm-wave is a new region and how the channel model is built makes a big difference.

6.1 Simulation Procedure

Simulation procedure is depicted in Figure 6.1. First, same as how a normal simulator works, cells and UEs are constructed by referencing some predetermined parameters. Then a channel condition is generated between each (Cell, UE) pair. Using the channel condition generated, each UE can find the best (Cell, Beam) combination and use it as the association target. After association is done, we can apply any kind of scheduling strategy on the top of it. All simulation parameters are specified in Table 6.1 and Table 6.2.

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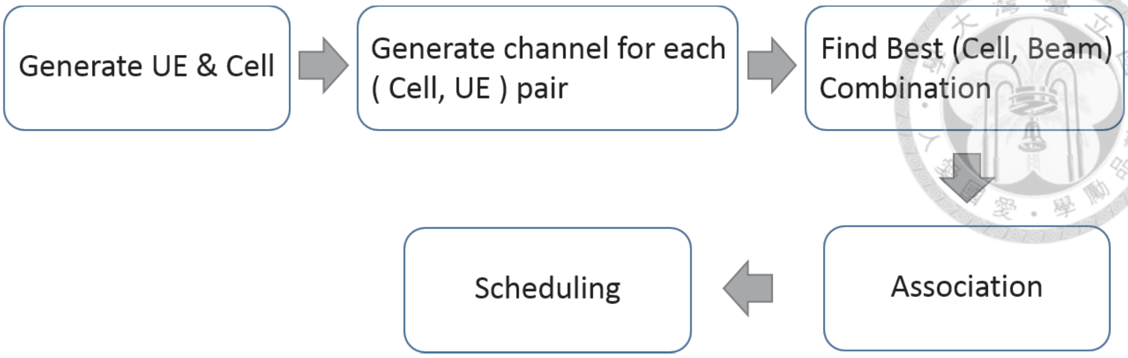

Figure 6.1: Simulation Flow

6.2 Channel Model

The construction of channel model in mm-wave band is essential. Now there are no 3GPP specification, or any other similar kind of document which restrict the way how people manage this issue. Since the possibility of mm-wave bands rise from the measurements conducted by Rappaport's team in NYU, we decide to reference their measurement results and build the channel model for our simulator for credibility.

There are two main parts of our channel model. The first part is large scale description: Path Loss(PL), Shadow Fading(SF). The second part would be the parameters for multipath feature (cluster characteristics). Combining these two parts we get a picture of the channel situation between the transmitter the receiver (Figure 6.2). Where P_r is the received power and P_t is the transmitted power. The ratio degrades as the distance gets farther.

In Figure 6.3, the procedure of generating a channel is shown, composed by large scale and multipath parameters, all referenced from [7]. Both static and dynamic procedure is presented. For moving UEs we develop a spatially consistent channel interpolation scheme(dynamic). However, our research problem only handles static users, so here we won't look into the the details of dynamic channel generation. If any extension of this work is needed, the dynamic channel generation could be of great help. The static proce-

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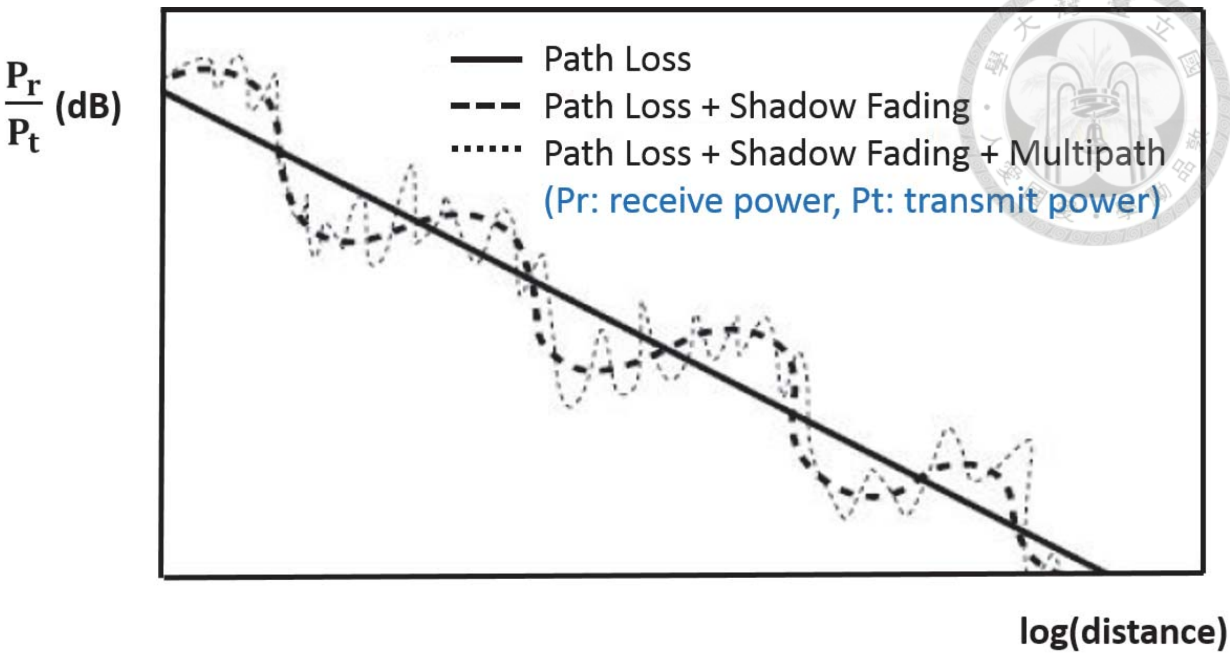

Figure 6.2: Overall Channel Description

dure is the same as [3]. Most of the parameters in Figure 6.3 are included in [7]: Delay Spread (DS), Angle(Spread), K (for LOS scenario), etc, and note that these parameters are intended for **NLOS** scenario.

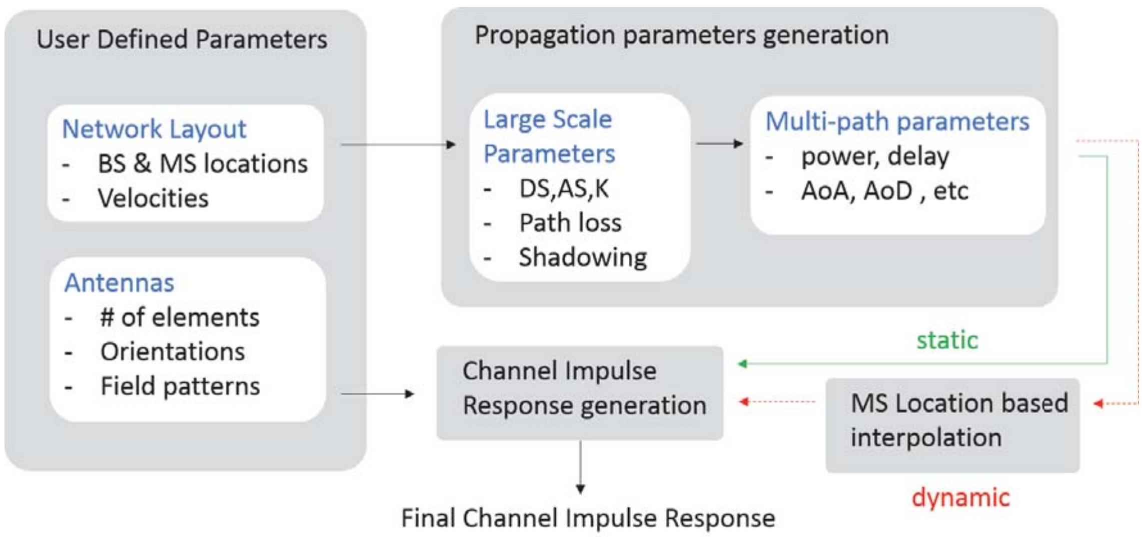

Figure 6.3: Channel Generation Flow [3]

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6.2.1 Model of Path Loss & Shadow Fading

For path loss model we describe it through a standard linear model:

$$PL(d)[dB] = \alpha + 10\beta log_{10}(d) + \xi$$
$$ShadowFading : \xi \sim \mathcal{N}(0, \sigma^2) \quad (6.1)$$

Equation 6.1 is the effect of both Path Loss and Shadow Fading (ξ). d is the distance in meters, and α and β are the least square fits of floating intercept and slope over the measured distances, and σ^2 is the lognormal shadowing variance. The value of α,β and σ^2 are shown in Table 6.1. Figure 6.4 is the scatter plot that is used in [7] to do the fitting procedure, and we only adopt the 28GHz NLOS part.

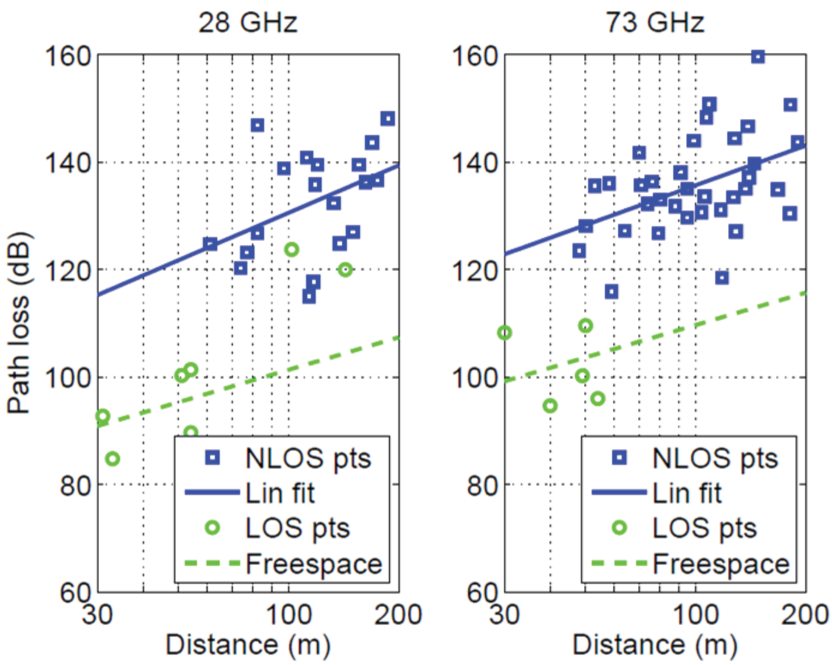

Figure 6.4: Scatter plot along with a linear fit of the estimated path losses as a function of the TX-RX separation for 28 and 73 GHz

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6.2.2 Model of Multipath feature

For multipath feature, there is a well known channel model for MIMO scenario simulation which is stated in [3], normally we call it Spatial Channel Model (SCM). It is reasonable to adopt SCM as the base of our channel model, because at the cell side we use multiple antenna elements and beamforming technique just as in MIMO. Moreover, nearly all the parameters needed for generating SCM are shown in [7], so we can replace those parameters and generate a MIMO channel model for mm-wave band.

The basic concept of SCM for signal cluster is the imagination of multiple paths between the transmitter and the receiver (Figure 6.5). Each path will have a central angle, and many subpaths spread from the central angle in a certain distribution. These paths represent the imaginary channel in the air and has nothing to do with the antenna elements. The central angle at the transmitter side is called Angle of Departure (AoD) and has horizontal/vertical components. While Angle of Arrival (AoA) is the angle at the receiver side, which also has horizontal/vertical components.

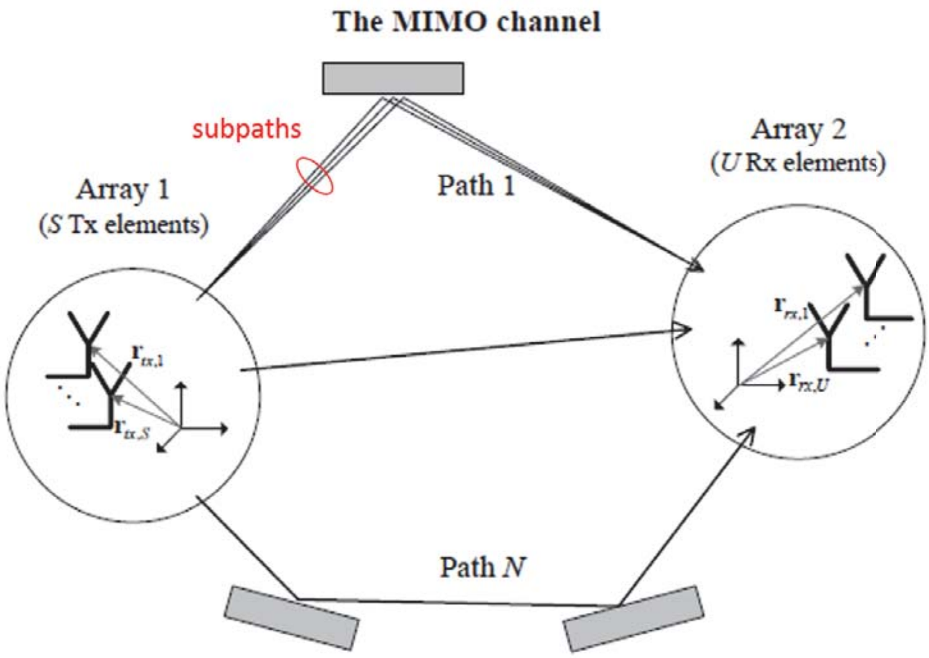

Figure 6.5: Spatial Channel Model [3]

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Due to the different arrival and departure angles, antenna elements encounter distinct propagation length of signals and lead to phase discrepancy. The distinct phases may cause constructive or destructive effect according to the angles. On the other hand, horizontal/vertical components of AoD also result in different field gain as stated in chapter 3. Still another effect is the random phase in each subpath. All of these effects can be integrated into a channel matrix **H** which well describe the imaginary channel in the air. The concept of H aggregating all spatial domain characteristics is shown in Figure 6.6, as well as some of the essential parameters. After H is found, beamforming can be performed and see which beam contributes to the desired UE the best. The calculation equation of **H** is in Figure 6.7, simplified from the equations in [3]. **H** is calculated for each (Tx element, Rx element, path) group, the summation over subpath is to aggregate the effect of each subpath since the signals from the same path will arrive at the same time.

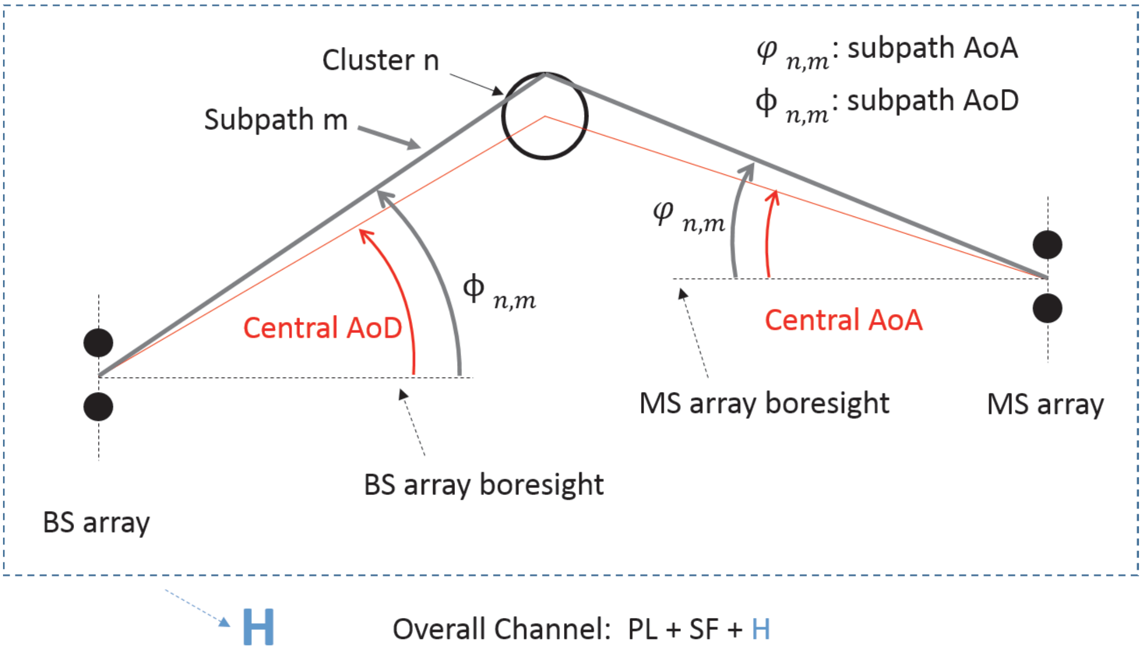

Figure 6.6: H aggregating many features [3]

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Random phase

Rx Field pattern

Tx Field pattern

$$\mathbf{H}_{\mathrm{u,s,n}}(\mathrm{t}) = \sqrt{\frac{\mathrm{P_n}}{\mathrm{M}}} \sum_{m=1}^{M} [F_{rx,u}(\varphi_{n,m})][\exp(j\Phi_{n,m})]\,[F_{tx,s}(\phi_{n,m})]$$

$$\cdot \exp(jd_u 2\pi\lambda^{-1} \sin(\varphi_{n,m})) \cdot \exp(jd_s 2\pi\lambda^{-1} \sin(\phi_{n,m}))$$

Phase shift due to element spacing

Figure 6.7: Channel Matrix Calculation [3]

6.3 Power Calculation

Section 6.2 describe how mm-wave channel model is generated. In this section we illustrate how we get the intended signal or interference power from the channel generated before.

As stated in chapter 3, the pattern of beams beamformed by the cell antenna array is pre-determined. Each beam direction will have a set of weights for all the antenna elements, and by multiplying these weights with channel matrix (H), beamforming effects can be calculated. We name the result after multiplying beamforming weight with H to be the **beam-formed channel response**, which might vary due to different beam directions (Figure 6.8).

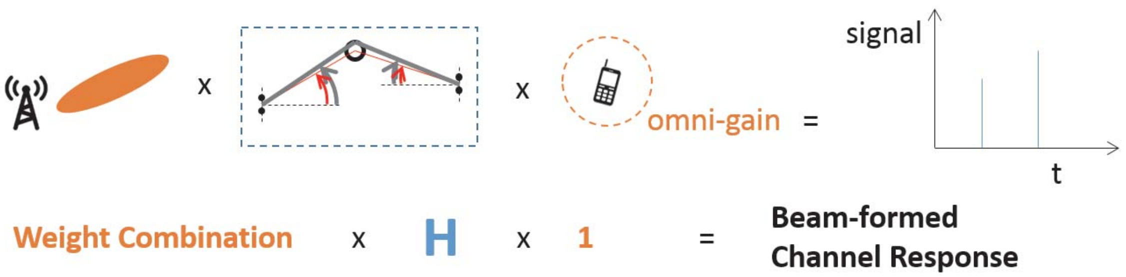

Figure 6.8: Beam-formed Channel Response Generation

We calculate the received power gain from the beam-formed channel response for each

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beam direction. Signal strength gain from each path will be squared to get the power gain, then each path's power gain will be summed up to get the overall power gain (Figure 6.9). We call this power gain **beam-formed channel gain**.

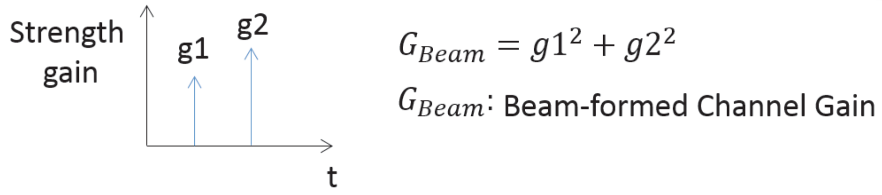

Figure 6.9: Beam-formed Channel Gain Calculation

The received power then can be calculated by the following equation:

$$P_r = P_t + G_{Cell} + G_{Beam} + G_{UE} - (PL + SF) \tag{6.2}$$

Where:

P_r: Received power, P_t: Cell transmission power

G_{Cell}: Cell antenna element gain, G_{UE}: UE antenna element gain

G_{Beam}: Beam-formed channel gain, PL: Path loss, SF: Shadow fading

In this equation cell power and element gain is added, and the channel part including beam-formed channel gain and large scale (PL, SF) components are also added to get the final received power. When a UE proceed association, it connects with the best (cell,beam) pair, which gives him the maximum received power as calculated by equation 6.2. We list the rest of the simulation settings in the tables below.

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Table 6.1: **Channel Model Related Settings**

Variable	**Model**	**Parameter values**
Omnidirectional Path Loss (PL) & Shadow Fading (SF)	PL = $\alpha + 10\beta log_{10}(d) + \xi[dB]$ $\xi \sim \mathcal{N}(0, \sigma^2)$	$\alpha = 72, \beta = 2.92,$ $\sigma = 8.7$ dB
Number of clusters, N	Fixed Value	N = 2
BS and UE horizontal cluster central angles, θ	Uniform Distribution	$\theta \sim \mathcal{U}(0, 2\pi)$
BS and UE vertical cluster central angles, ϕ	Fixed Value	$\phi =$ LOS elevation angle
BS cluster angular spread	Fixed Value	Horiz = 10.2° Vert = 0°
UE cluster angular spread	Fixed Value	Horiz = 15.5° Vert = 6°
Cluster power fraction	$\gamma'_k = {U_k}^{r_\tau - 1} 10^{0.1 Z_k}$ $Z_k \sim \mathcal{N}(0, \varsigma^2), U_k \sim \mathcal{U}[0, 1]$	$r_\tau = 2.7, \varsigma = 4$

Table 6.2: **Other Network Basic Settings**

Parameter	**Description**
BS layout and sectorization	Hexagonally arranged cell sites with 3 cells per site
UE layout	Uniformly drop 200 UEs in each site
Inter-site Distance(ISD)	200m (may change in different simulations)
Carrier freqency , Bandwidth	28GHz , 1GHz
Transmission mode	Only Downlink
Traffic model	Full buffer
Multiple access	UE takes the whole bandwidth w/o frequency division, but support multi-user beamforming
Transmit power	37 dBm (downlink)
Cell antenna format	8x1 λ/2 uniform planar array
Cell antenna element	Gain pattern: reference from [3], HPBW = 65°, maximum gain at the center: 10 dB
UE antenna format	1 antenna element
UE antenna element	Omni gain: 0 dB
Cell beamforming	8 determined directions, support multi-user beamforming
Noise density	-174 dBm/Hz
Capacity evaluation	Use shannon capacity: $C = Blog_2(1 + SINR)$

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Chapter 7

Simulation Results

Finally we get to this chapter. Results of the simulation are shown in this chapter, first its for TDMA scenario. Then we discuss about the results for simultaneous beamforming, both cell resource allocation and interference management. Basic settings are in chapter 6 but we might adjust some variables to see the trend of some certain features. Several metrics will be used including, aggregate cell throughput, user throughput CDF, cell-edge user throughput, fairness index.

7.1 Results for TDMA

Recall in chapter 4, we decide to deal with intra-site interference. Which is the interference from the cells in the same site with the concerned cell. After that we proposed **Intra-site Aware TDMA** for TDMA scenario to decrease the intra-site interferences. Now we compare the results with just using TDMA without our scheme.

First in Figure 7.1, we compare the aggregate throughput between the two method and changes the ISD to observe the trend. From the figure we can tell that **Intra-site Aware TDMA** outperforms **TDMA** interms of throughput. We expect a throughput degrade for

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Intra-site Aware TDMA in condition1 because some UE and beam choices are taken out, but only a small gap between the two method happens in condition1 under ISD 100(m). This means that the maximum 20dB threshold well preserved the freedom of selection.

We further investigate on other metrics too see if there is any sacrifice for this throughput increase. Fairness might be harmed under the algorithm we developed, because eliminating some choices from other cell intuitively affects the original allocation order. In Figure 7.2 we show the Jain's Fairness Index of these two method. It is suffice to say that there is nearly no difference. High SNR users are more sensitive to intra-site interferences, so in both method the fairness increases in condition2. The low value of fairness index results from the SNR distribution.

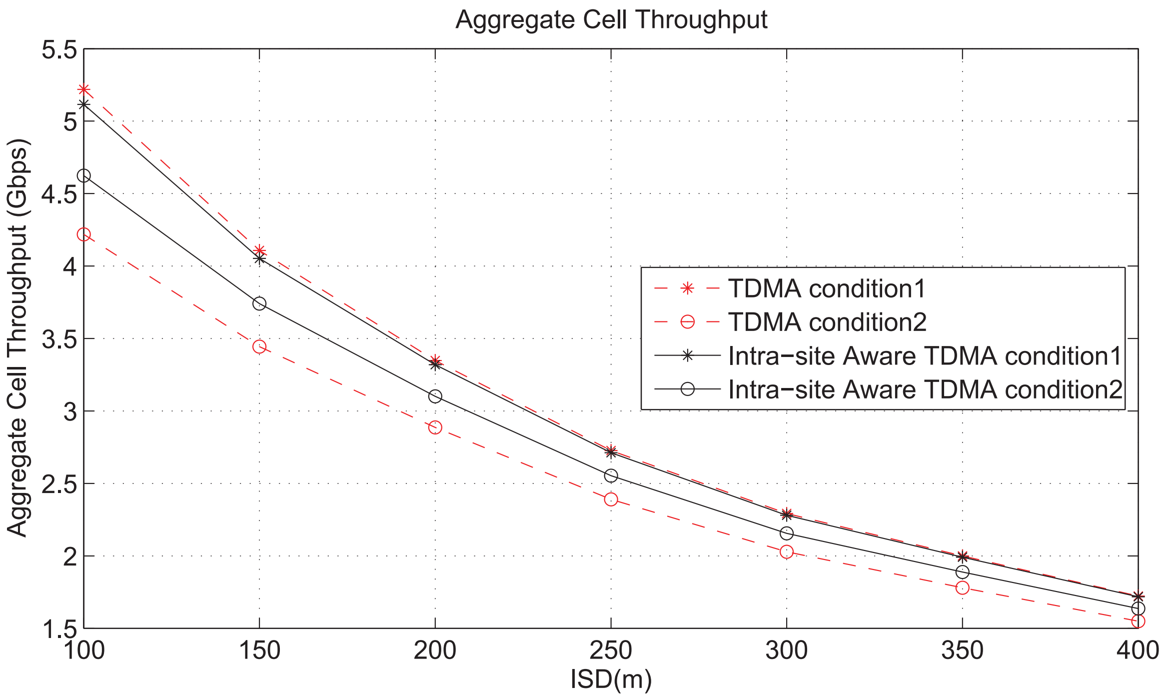

Figure 7.1: Aggregate Throughput of TDMA & Intra-site Aware TDMA

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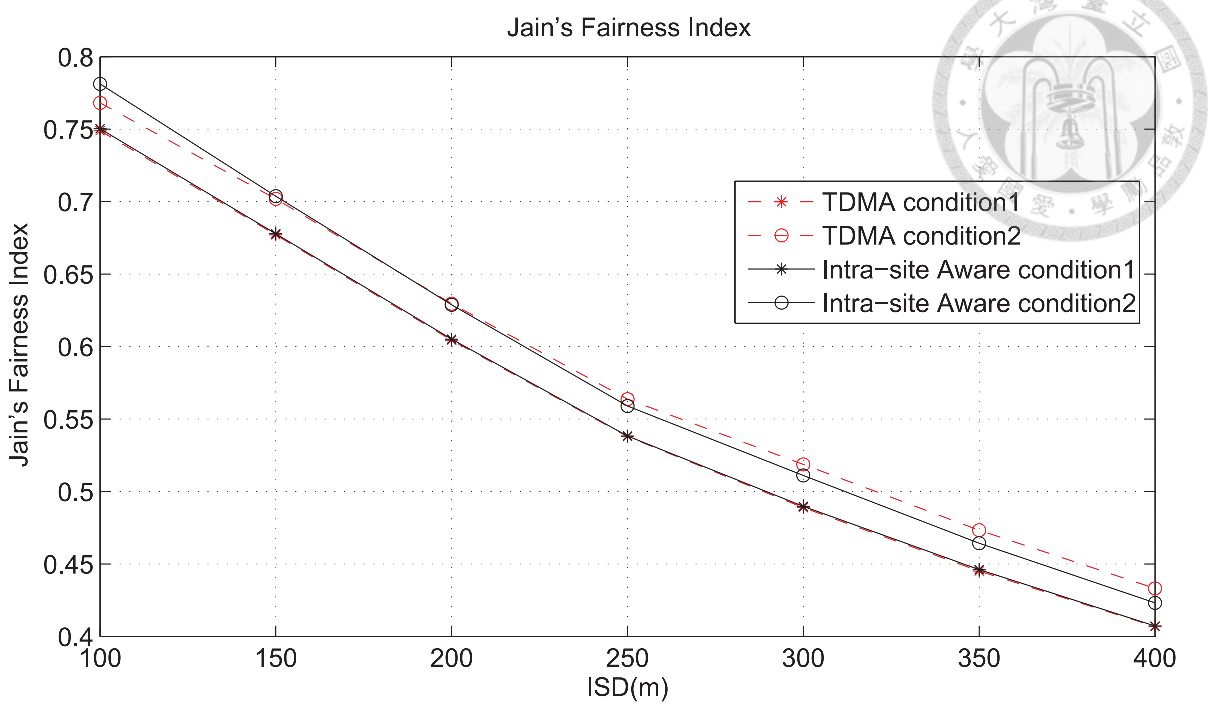

Figure 7.2: Jain's Fairness Index of TDMA & Intra-site Aware TDMA

7.2 Results for Simultaneous Beamforming

Two kind of cell resource allocation method for MU-beamforming scenario are introduced in chapter 5. **Basic Orthogonal Channel-based Method**(BOCM) purely considers inra-cell beam interferences, and on the other hand **Intra-site Aware Orthogonal Channel-based Method**(IAOCM) additionally take other cell's scheduling results into account and avoid possible collisions.

7.2.1 Resource Allocation Within a Cell

First how well the BOCM can utilize the spatial domain resource inside a cell should be examined. In chapter 4, Figure 7.3 is showed to explain our motivation (MU-Beamforming uses BOCM), here we examine it again to compare with just TDMA method. When we focus on condition2, which is the scenario we chose to solve, it reveals that BOCM achieves about 36% more throughput when we calculate the exact numbers at ISD 200(m). Other

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settings of ISD(m) also have similar percentage of increase. However, higher than TDMA is expected and not difficult, so we further use the two baseline **Greedy Algorithm** & **ChangYu** proposed in chapter 5 to see the spatial reuse performance (Figure 7.4).

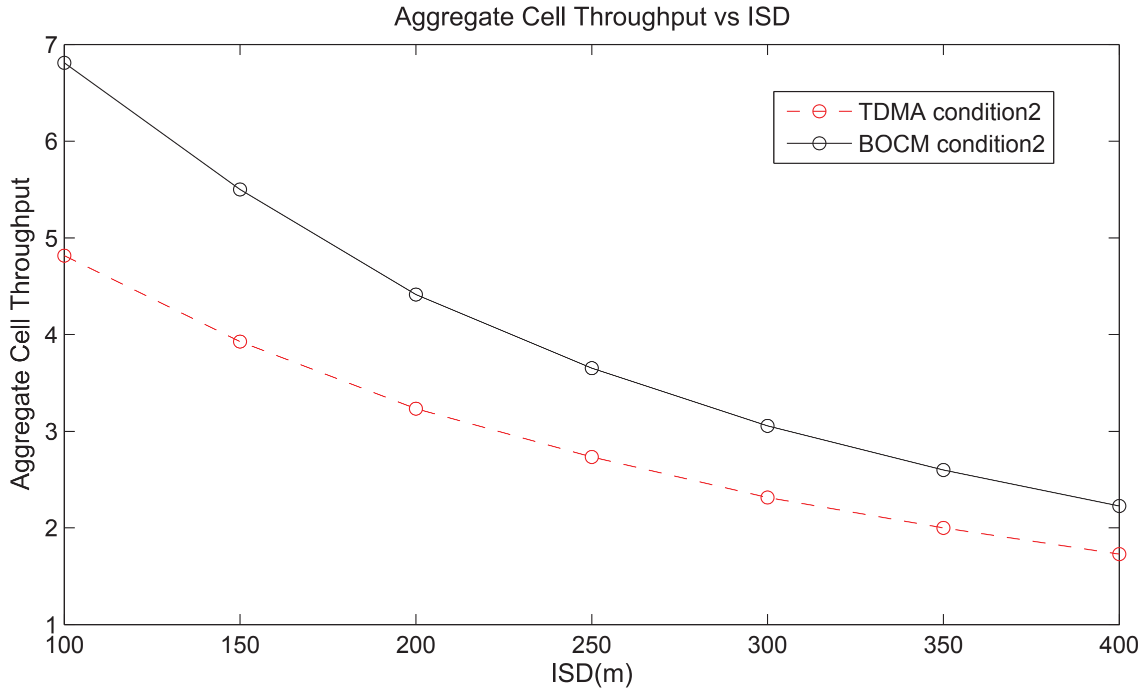

Figure 7.3: Spatial Reuse Performance

In Figure 7.4 for both condition1 & condition2, the trend is alike. Greedy higher than BOCM, and BOCM higher than ChangYu, TDMA is always the lowest as expected. Compare BOCM with ChangYu, BOCM not only outperforms in terms of throughput, the computing overhead is also smaller. A possible cost of Greedy in order to achieve such high throughput is fairness, so we look into the fairness of these algorithms in Figure 7.5 & Figure 7.6. It is obvious that TDMA has the highest fairness and BOCM, ChangYu has the same level of fairness, while Greedy has lower fairness.

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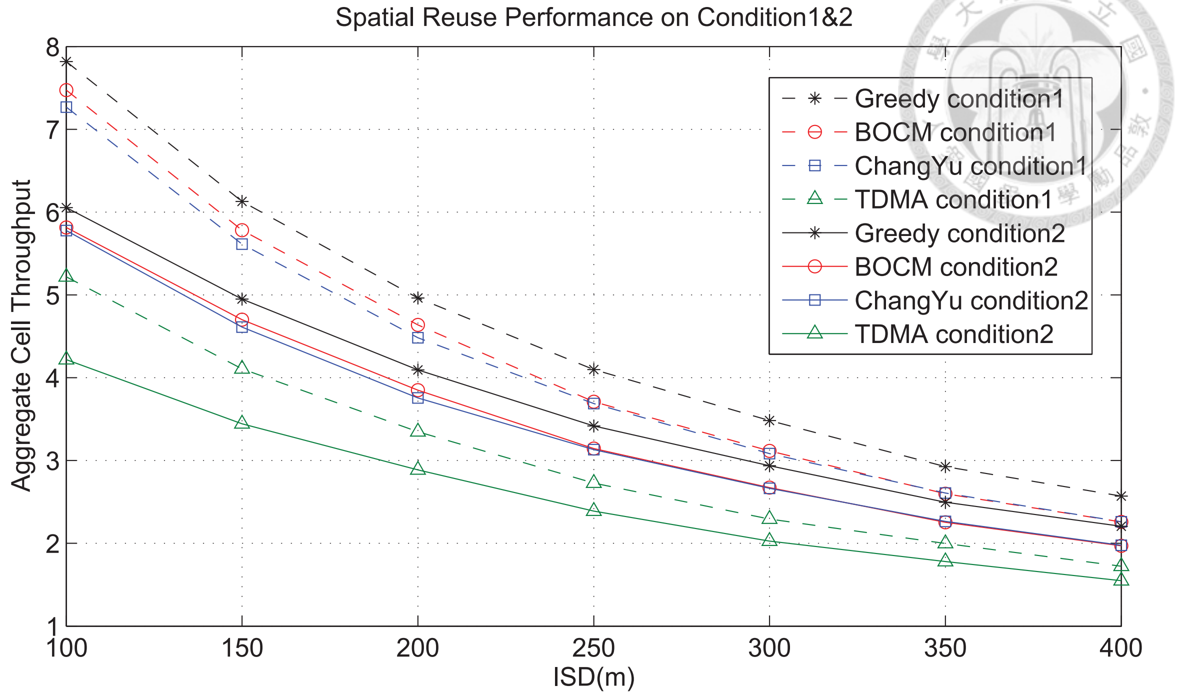

Figure 7.4: Spatial Reuse Performance with Baseline

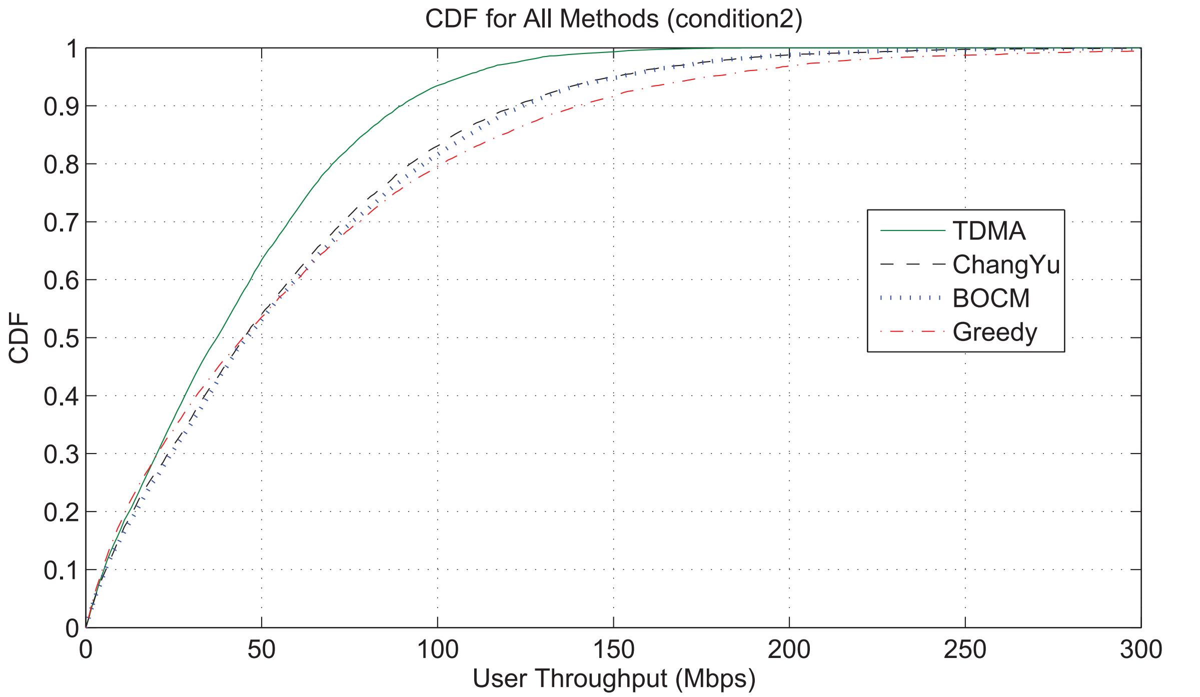

Figure 7.5: CDF for Spatial Reuse Performance (ISD 200m,condition2)

7.2.2 Interference Management

We have checked the spatial reuse performance of BOCM, now we go on to see the performance of IAOCM when interference is faced. IAOCM is based on BOCM and add sev-

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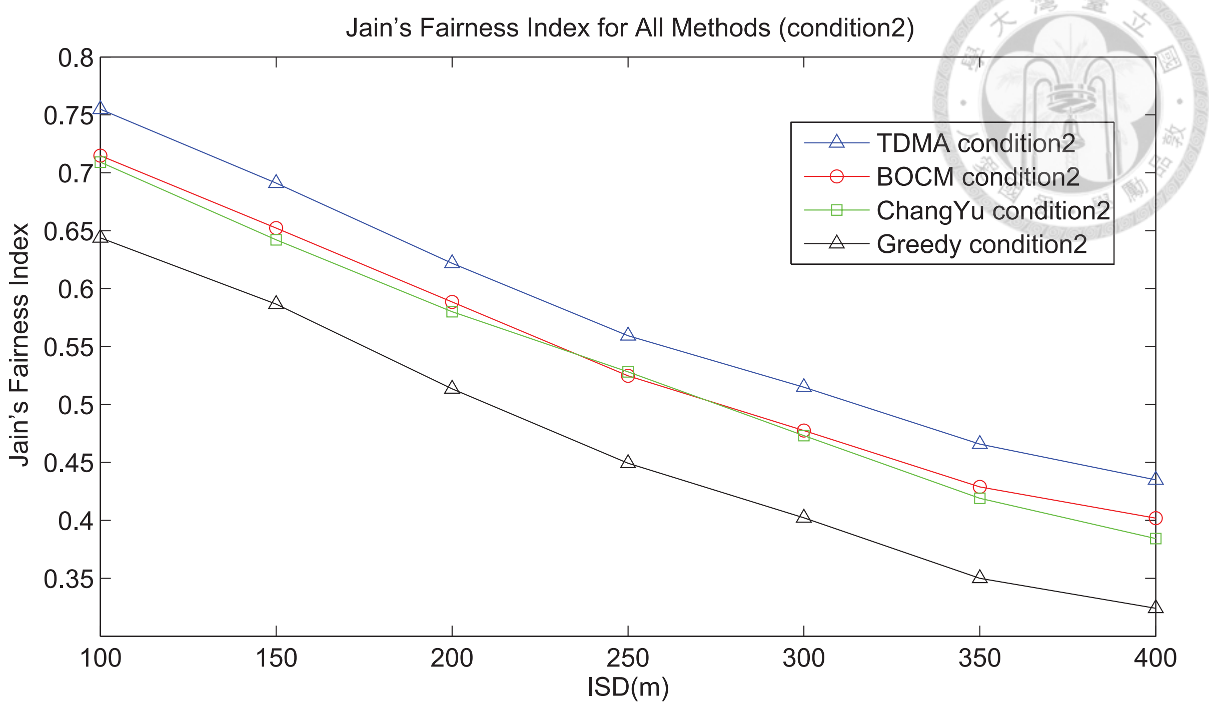

Figure 7.6: Jain's Fairness Index for Spatial Reuse Performance (condition2)

eral additional rules to prevent possible collisions. Since the algorithm ChangYu has the same level of performance with BOCM but is more complicated in calculation, we don't compare with ChangYu in this subsection. Aggregate throughput of IAOCM is shown in Figure 7.7. IAOCM rise to the throughput level of Greedy. In smaller ISD, IAOCM is higher and for larger ISD it is the other way around. This phenomenon can be explained as for smaller ISD, the interference is much higher and eliminating the collision choices finally outperforms Greedy, which only maximize the throughput inside its cell without considering other cells.

On the other hand Figure 7.9 shows the fairness index of IAOCM compared to other methods. IAOCM is slightly better than BOCM and close to that of TDMA, Greedy still hold the last place and is far away from the other three. Figure 7.8 is the CDF of all methods. To sum up, throughput of IAOCM is the same as Greedy and higher than BOCM. In terms of fairness index, IAOCM is slight better than BOCM and much better

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than Greedy. By eliminating possible collisions, IAOCM achieves certain improvements and performs well at smaller ISD settins, where interference is more critical. It is fair to say that for small ISD, IAOCM or Intra-site Aware TDMA can bring large benefits, and the interferences caused by strong signals of beamformed beams can be prevented with little efforts. Though collision probability is low, once the collision occurs, certain users/locations might experience devastating throughput loss, so overall throughput can not be the only measurement in the future.

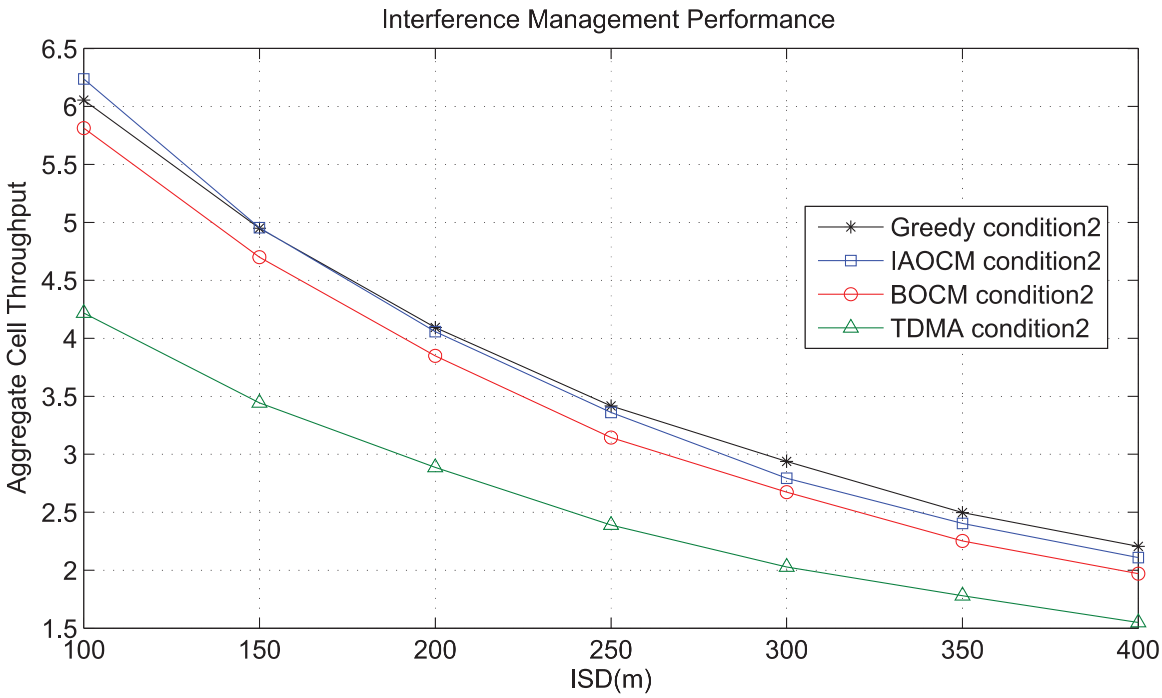

Figure 7.7: Throughput Performance for IAOCM

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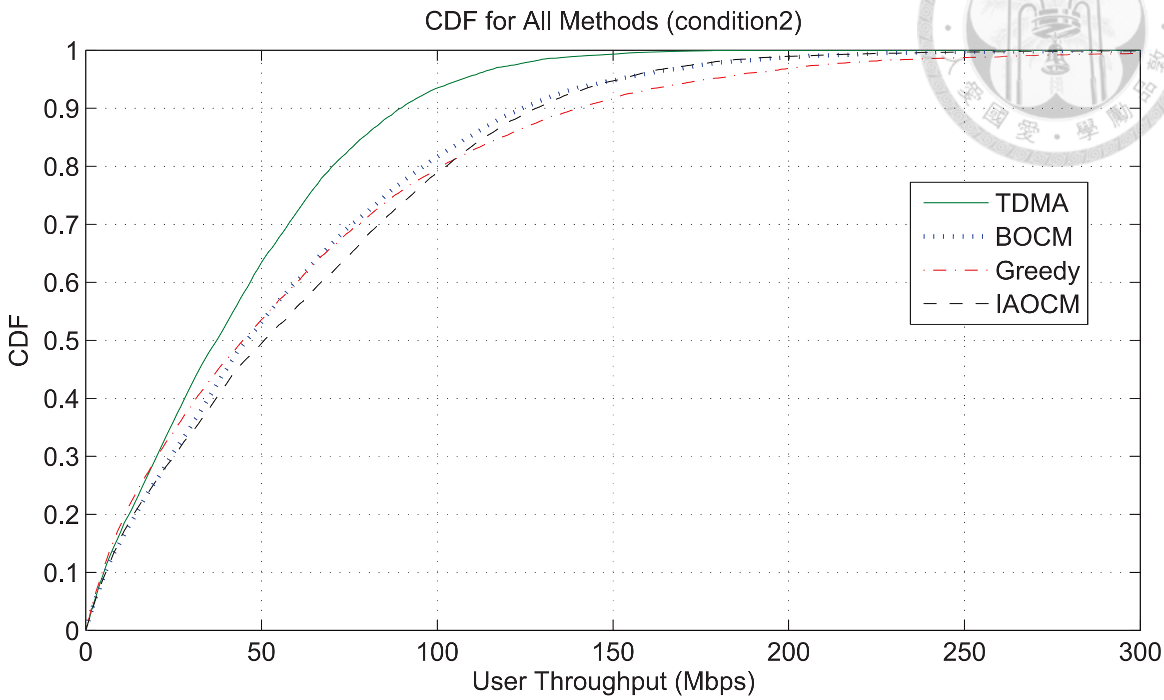

Figure 7.8: CDF for IAOCM and other Methods

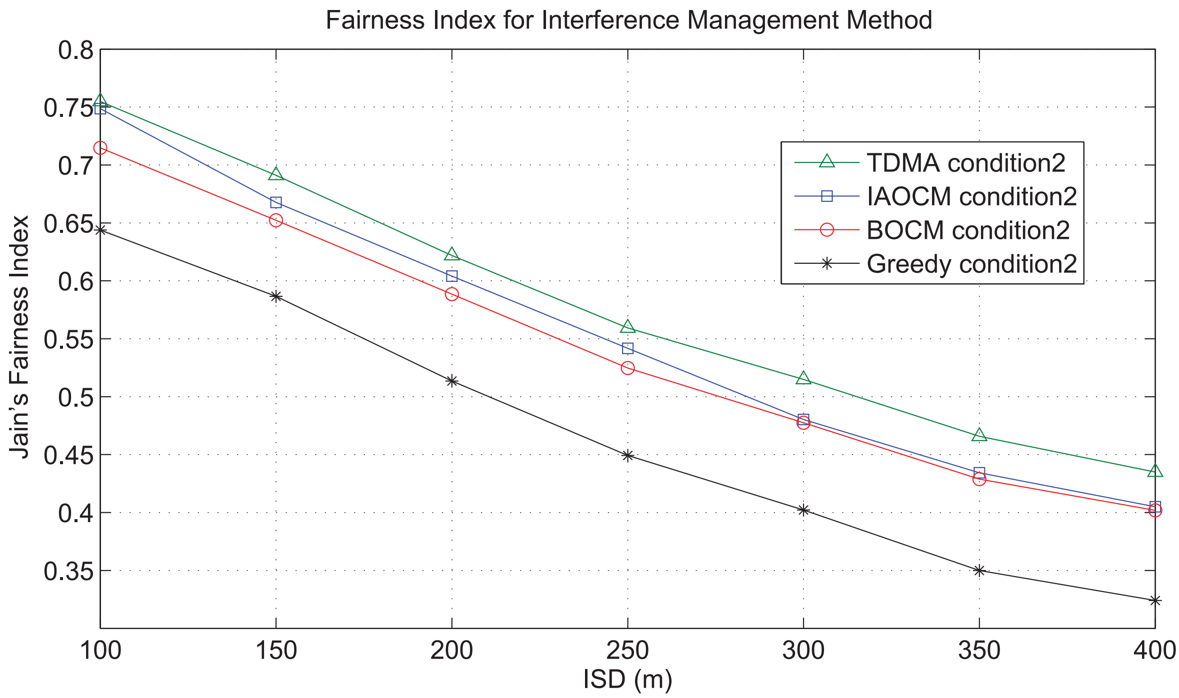

Figure 7.9: Fairness Performance for IAOCM

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Chapter 8

Conclusion

We have two main contribution under urban NLOS mm-wave cellular system scenario. In spatial-time domain resource allocation, we developed a simple orthogonality based method to perform the scheduling. This algorithm may suit code-book based beamforming well and has a high level of throughput close to the Greedy method mentioned in the article. In terms of fairness it is also better too.

For the interference part, we discovered that under the simulator settings, which is referenced from the newest measurement results, intra-site interferences might be a problem for future 5G mm-wave cellular systems. On the other hand, we also present a cell coordination method to solve this problem, again with the help of the orthogonality concept. In denser deployment scenario, this interference management can make a big difference. In the future, more solid channel models of mm-wave band will be specified and at that time, the features we found should be discussed again carefully.

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