國立臺灣大學資訊管理研究所碩士論文

指導教授：林永松 博士

# 考慮服務品質限制、整合語音與資料傳輸及頻寬切割之 WCDMA 基地台架設演算法

# A QoS and FDMA Constrained Base Station Deployment Algorithm in Voice/Data Integrated WCDMA Systems

研究生： 林明立 撰

中華民國九十三年十月

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本論文係提交國立台灣大學冸

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# 謝　詞

好容易才完成了這篇碩士論文。心中不免千頭萬緒、百感交集。一路跌跌撞撞地走來，而今終於畢業，要感謝的人實在是太多了… 對所有關心支持過我的人、請讓我在這裡先對你們說聲謝謝。

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# 論文摘要

論文題目：考慮服務品質限制、整合語音與資料傳輸及頻寬切割之

WCDMA 基地台架設演算法

作　　者：林明立　　　　九十三年十月

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無論是使用者或是電信業者都迫切地期待著第三代行動通訊的來臨，而本論文的目的在於提供電信業者一有效率的基地台架設演算法使其在知道使用者分佈的情況下得到最大利潤。

在 WCDMA 系統中，容量限制以訊雜比(signal-to-interference ratio, SIR)為主要依據，而本篇論文以能量為資源，加入頻寬切割之要素，依此設計出一基地台架設演算法，並讓電信業者能規劃出適當的頻寬切割方式。本論文針對 WCDMA 的系統，同時考慮上下行系統容量限制、漂亮地設計出此非線性問題並採用拉格蘭氏鬆弛法處理此一複雜問題而得到一令人滿意的結果。

**關鍵字：寬頻分工多重擷取系統(WCDMA)、基地台架設、容量管理、服務品質、第三代行動通訊系統、數學最佳化、拉格蘭氏鬆弛法。**

# THESIS ABSTRACT


**GRADUATE INSTITUTE OF INFORMATION MANAGEMENT**

**NATIONAL TAIWAN UNIVERSITY**

**NAME：MINGLI-LI LIN　　　MONTH/YEAR：OCT, 2004**

**ADVISER：YEONG-SUNG LIN**


## A QoS and FDMA Constrained Base Station Deployment Algorithm in Voice/Data Integrated WCDMA Systems


The diffusion and demand of mobile communication services are still growing rapidly nowadays. Users are no longer satisfied with merely speeches but eager to communicate with each other by multimedia services. That’s the reason why the approach to the base station deployment optimization problem is so urgent and important.

Many researches have been pronounced to solve the deployment problem. We combined the most important issues, such as downlink SIR constraint, uplink SIR constraint, soft handover, sectorization, and power control, frequency assignment into consideration.

We developed a mathematical programming model to describe this joint design problem. It turns out to be a non-linear non-convex mixed integer programming problem. A set of heuristic solution procedures based on Lagrangian relaxation methods is proposed to solve the complicated problem.



**Keywords: WCDMA , Base Station Deployment Algorithm, Quality of Service, 3rd**

**Generation Wireless System, Lagrangian Relaxation Method, Optimization, Mathematical Programming.**

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# Chapter 1 Introduction

## 1.1 Motivation

In recent years, the success of GSM (Global System for Mobile Communications, the 2nd Generation) has promoted more and more people using communication services. With the capacity and multimedia application requirements, the 3G (3rd Generation) wireless communications system is burgeoning. Service providers have been affording huge investments for network infrastructures and radio spectrum licensing cost. Therefore, a well-designed base station deployment model and solution in the 3G system is urgently needed. Many researches have made efforts in this area already and we integrate the important issues to build our model.

There are three basic multiple access schemes: frequency division multiple access (FDMA); time division multiple access (TDMA); and code division multiple access (CDMA). The multiple access schemes of GSM technique mixes TDMA and FDMA. The most promising multiple accesses technique that fulfill 3G wireless communications system is CDMA, and the CDMA core radio technique is DS-CDMA (Direct-Sequence CDMA)[16] . We discuss the problem in WCDMA which uses the DS-CDMA as a main technique and take the FDMA issue into consideration.

The problem of planning Base station placement in GSM cellular systems is broadly studied and has been matured which is usually simplified by subdividing it into a coverage planning problem and a frequency planning problem. Considering the 3G environment, the situation becomes much more complex due to the basic technique difference. We design the models including suitable parameters and constraints to solve the problem. The detail will be discussed in the next few sections.

The network planning and capacity management includes five major modules depicted in Figure 1-1.

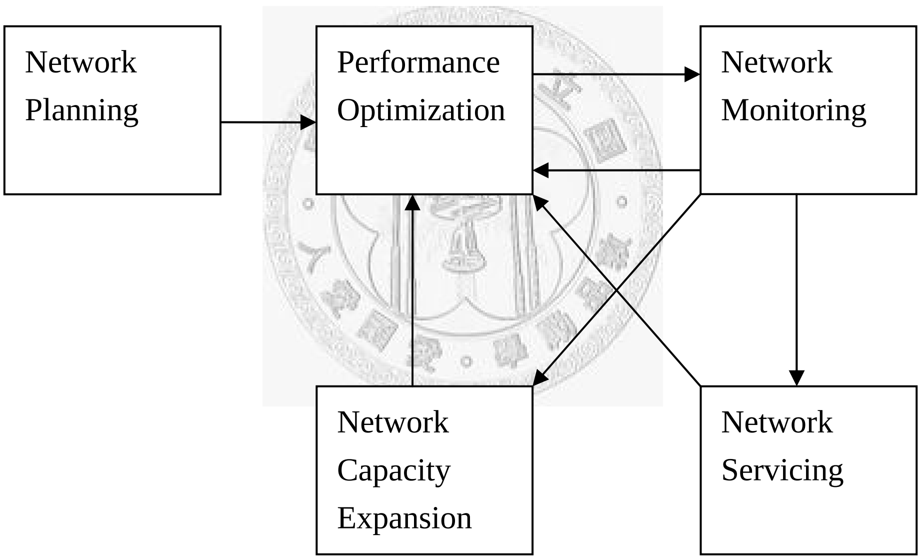



Figure 1-1 Operation support and capacity management model

This thesis will focus on the Planning, Optimization and Network Capacity Expansion issues.

## 1.2 Literature Survey

### 1.2.1 WCDMA technique

In FDMA (frequency division multiple access) system, it employs difference carrier frequency to transmit the signal for each user. In TDMA (time division multiple access) system, it uses distinct time to transmit the signal for difference users. In CDMA (code division multiple access) system, it uses different code to transmit the signal for each user. Contrary to FDMA and TDMA, CDMA makes all users share the same radio frequency at the same time by using ‘code’ to separate different channels.

Direct Sequence Code Division Multiple Access (DS-CDMA) technique is adopted as an air interfaces multiple access scheme in 3G systems. In DS-CDMA, user information bits are spread over a wide bandwidth by multiplying the user data with quasi-random bits (called chips) derived from CDMA spreading codes. By spread spectrum, the original information becomes a thin and ineffective slip of noise transferring to the receiver (Figure 1-2). In other word, the wideband signal can be below the thermal noise level. When the receiver receives the modulated signal, it can decode it to get the correct information with the PN code of this connection. [4]

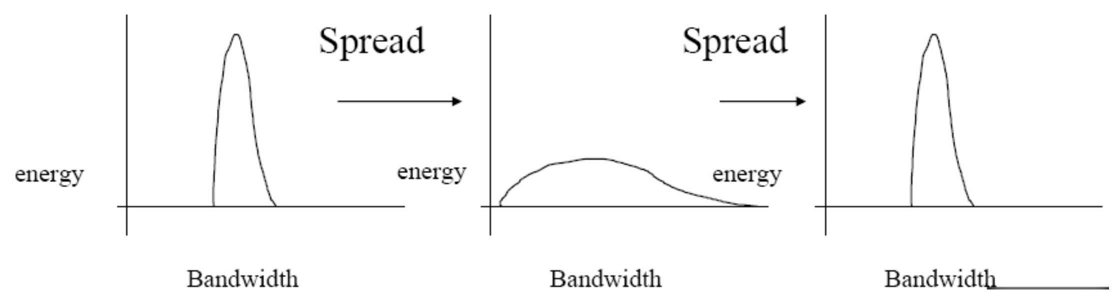


Figure 1-2 Concept of direct sequence spread spectrum

WCDMA, standardized by 3GPP (The 3rd Generation Partnership Project), uses one 5

MHz frequency band to provide higher data rate services and better coverage, it can support very high bit rates (up to 2 Mbps) and also can support highly variable user data rate.

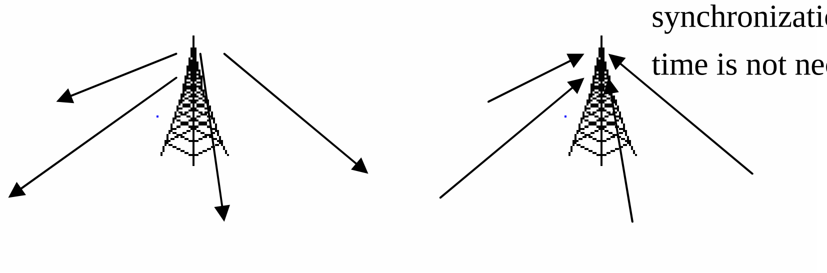



Figure 1-3 Downlink and Uplink Signal

The downlink signal transmitted in WCDMA is the same with the original method. The base station transmits a combined signal power and the mobiles decode the signal with their own code. There is a little difference in the uplink. The mobiles are not necessarily transmitting signals at the same time in WCDMA. Instead, they transmit freely and let the rake receiver take the job to select the correct signals.

### 1.2.2 WCDMA interference model, capacity issue

No absolute number of maximum available channels is the main difference between CDMA to the other mechanisms. The system is typically interference-limited [4] . We have to calculate the amount of interference to make sure that in both uplink and downlink direction the signal to interference ratio is satisfied. Signal-to-interference ratio (SIR) is the ratio of the power of the wanted signal to the total residue power of the unwanted signals which are also called interference. In order to correctly derive the wanted code, the SIR must be above a given threshold.

In WCDMA we use $E_b / N_0$, energy per user bit divided by the noise spectral density to represent the SIR [4] .

$$(E_b / N_0)_j = \text{Processing gain of user(or base station) } j * \frac{\text{Received Signal in } j}{\text{Total received power (exclude needed signal)}}$$

The major interference to a given cell includes inter-cell interference, intra-cell interference and thermal noise. The thermal noise is the background noise that exists in nature. In uplink, the intra-cell interference including inter-cell interference is the total power received at the base station excluding the wanted mobile power. In downlink, the intra-cell interference is the fading effect [4] and the inter-cell interference is the total power received at the mobile from all other base stations.

A base station has maximum total transmission power constraint, and so does the mobile station. The total system capacity will be limited by power constraint. There are two estimation ways to calculate the capacity [6] [12] , but we calculate the power and interference in the original way in order to get the most accurate result.

"Where is the bottleneck in WCDMA." is an interest question. In the past, we usually set the uplink as the critical point and we could see many researches recently set the downlink as the bottleneck. In [14] , we know that the both uplink and downlink should be considered at the same time in the indoor situation. We calculate the both way in this thesis to make sure both uplink and downlink SIR is satisfied.

### 1.2.3 Frequency assignment issues

FDMA is a well-known schema to avoid interference. We take the FDMA issue in this thesis into consideration.

As mentioned, WCDMA system is interference-limited and power-limited. The FDMA would directly affect the power (interference) issue.

It would be easier to get the whole picture through an example.

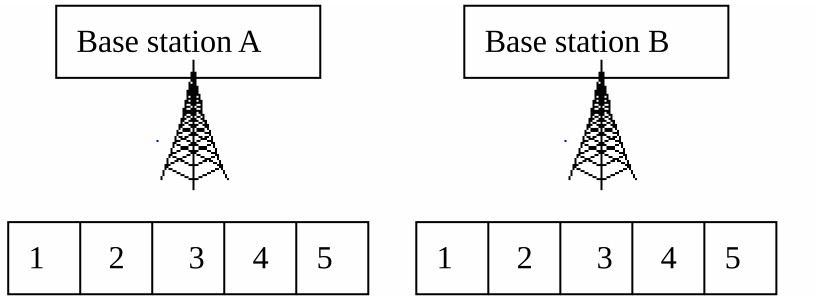



Figure 1-4 FDMA issue

The frequency effect could be easily formulated below.

$$\text{Interference} = \text{Unwanted power} * \frac{\text{Mutually covered frequency}}{\text{Frequency of the unwanted power source}}$$

For example, if the base station A uses the 1, 2 and 3 frequency, and base station B uses the 2, 3, 4, and 5 frequency. The mutually covered frequency is 2 and 3, which is 2 frequencies. We could calculate the interference mobile stations served by base station B received is $(\text{power from A}) * \frac{2}{3\text{(A uses 3 frequencies)}}$ and the interference mobile stations served by base station A received is $(\text{power from B}) * \frac{2}{4\text{(B uses 4 frequencies)}}$.

## 1.2.4 Relative Works in 3G Base Station Deployment

The base station deployment problem with power control is a NP (nonpolynomial)-hard problem [2] . Heuristic algorithms have been proposed in [3] , and many works use simulations to solve this problem.

It would be much easier to solve the problem using simulation, but the approach would be much passive as well.

For example, the process in [3] is described in Figure 1-5

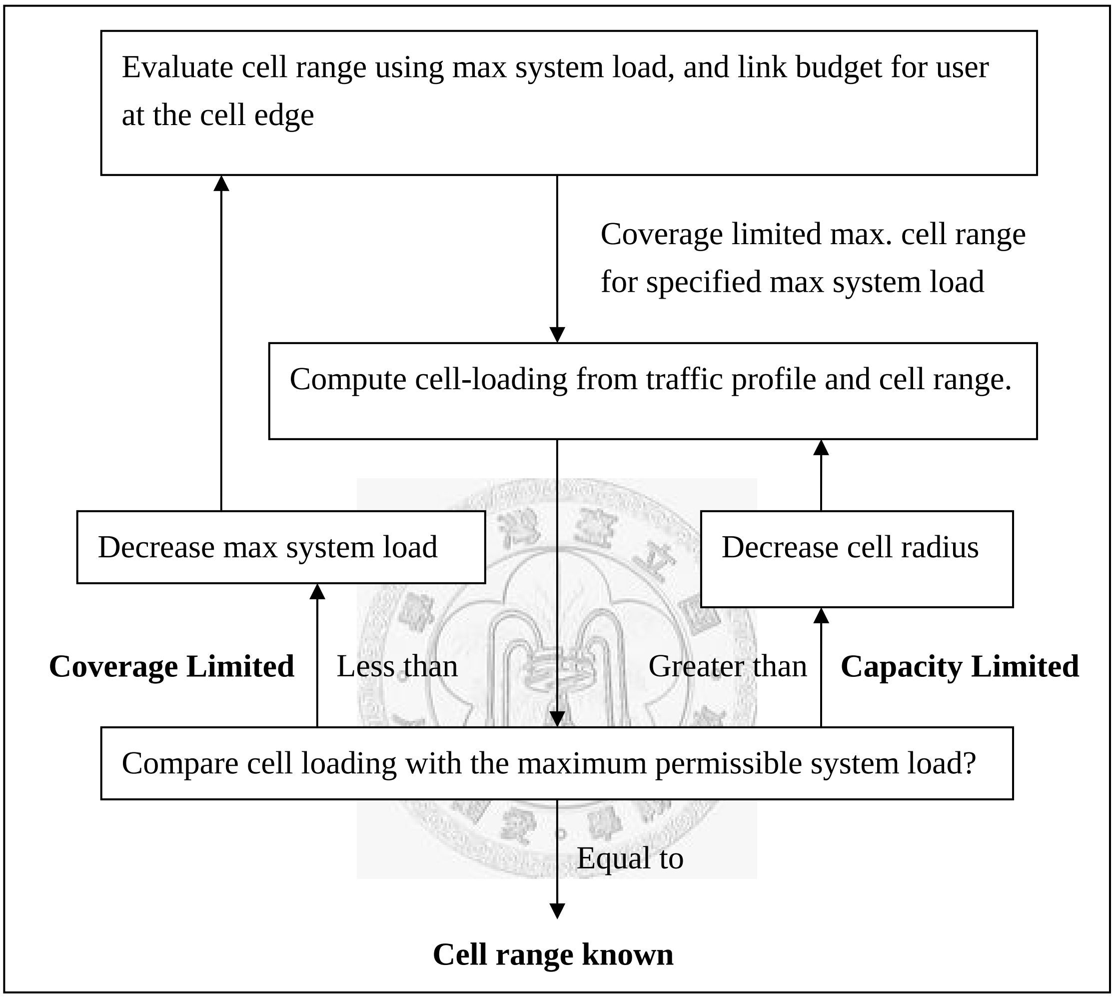



Figure 1-5 simulation method solving deployment problem

Iteration by iteration, we could find the solution, but optimization is not guaranteed. Instead, our model guarantees the optimization.

Our model is based on the same concept of[16] , and adds the downlink budget concept in[17] and take the power constraints further.

## 1.2.5 Soft Handoff

Soft handover was introduced by CDMA technology. In order to decrease the handoff time, increasing the SNR (signal to noise ratio) by the combining of the diversity signals [5] [8] , and decrease the outage probability when the transmission power is constant [8] [10] . We use SHO (soft handover) in WCDMA instead of HHO (hard handover) in GSM system.

**Soft handover gain from the decreasing of the outage probatility:**

The soft handover gain and the increase in downlink coverage are considered in [10] . The soft handover gain is due to the probability of outage caused by slow fading.

Consider the scenario described in Figure 1.6

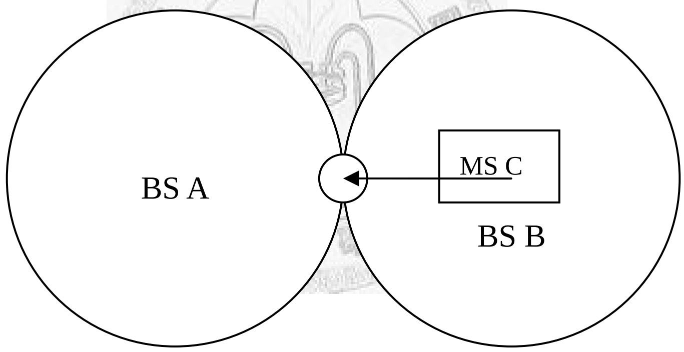



Figure 1-6 Soft Handover decrease outage probability

When mobile terminal C is on the edge of the two base stations, the HO (handover) occurs. Due to slow fading, which is caused by multi-path, there would be an outage probability for SIR requirement is not satisfied. The difference between HHO and SHO is discussed below.

HHO situation: The MS C can only connect one of the BSs. Therefore, there would be an outage percentage decided by the connected BS transmission power. If we want the outage percentage below the acceptable value (e.g. 5%), the connected BS transmission power should be added to a margin value. The margin value is well known as ‘hard handoff margin’.

SHO situation: The MS C could connect to both BS A and BS B on the edge. Therefore, the outage percentage should be incorporated. The outage percentage in SHO is calculated in [10] . It is the joint probability. And the upper bound of the soft handover margin is pronounced.

**Soft handover gain from the combining signal power:**

The process is not the same in the different transmission directions. In the uplink, the mobile transmits the signals through its omni-directional antenna. The base stations in the active set can receive the signals simultaneously because of the frequency reuse factor one in CDMA systems. Then, the signals are passed forward to the RNC [4] for selection. The better frame is selected and the other is discarded. Therefore, in the uplink, there is no extra channel needed to support soft handover. In Figure 1-7, the best signal from BS2 is selected and the other two signals from BS1 and BS3 is discarded.

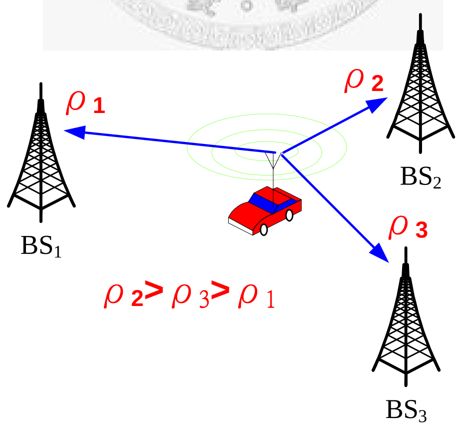



Figure 1-7 Selection Combining of Soft Handover in Uplink[19]

In the downlink, the same signals are transmitted through both base stations. The mobile can coherently combine the signals from different base stations since it sees them as just additional multi-path components, like Figure 1-8. Normally maximum ratio combining strategy is used, which provides an additional benefit [5] . However, to support soft handover in the downlink, at least one extra downlink channel (2-way SHO) is needed.

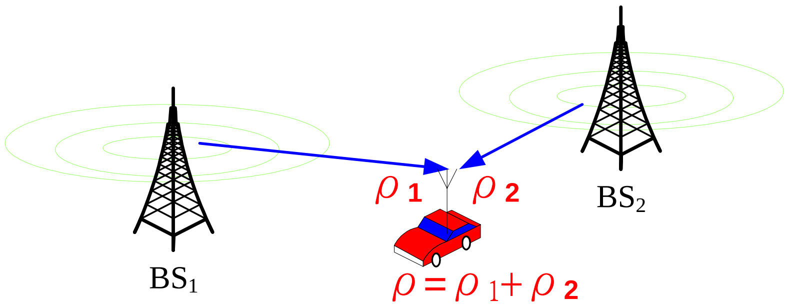



Figure 1-8 Maximum Ratio Combining of Soft Handover in Downlink[19]

**Soft handover overhead:**

The cost of SHO is the soft handover overhead, which is caused by the second connection. When SHO occurs, the second connected BS must assign a channel to the MS in the downlink and thus occupy an overhead resource. As a result, in the downlink direction, the performance of the soft handover depends on the trade-off between the macro-diversity gain and the extra resource consumption[19] .

## 1.2.6 Sectorization and Softer handoff

Softer handover is similar to soft handover. The main difference between softer handover and soft handover is the connection site number. During the soft handover, MS connects to 2 or more sites. MS connects to only one site during the softer handover.

The impact of the base station sectorization on WCDMA is proposed in [13] [18] . The technique is used in most of the GSM system, and causes different influences in GSM and WCDMA system.

Consider Figure 1-9 below

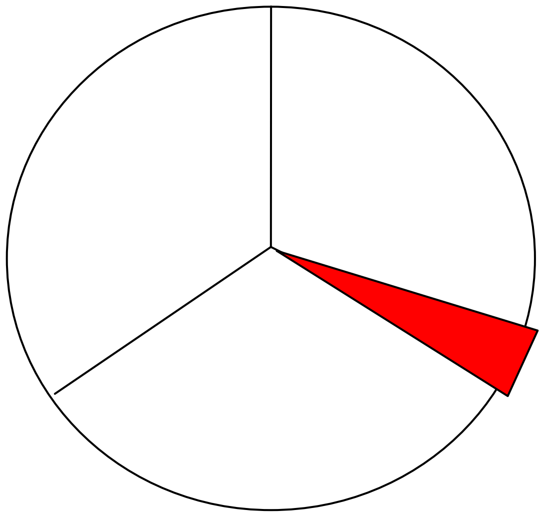


Figure 1-9 sectorization

The BS is divided into 3 sectors and each sector could be thought as a complete cell for the frequency of the sector is not to be divided. The sector number should increase the capacity linearly in theory (the number of users of sectored site divided to the number of users of omni site is well known as 'sectorization gain'). But the leaky signal between sectors causes additional interferences and softer handover overhead. The simulation experiment result in [13] shows that the antenna should be well chosen to decrease the overhead.

When the sector is considered, the softer handover overhead should be considered as well, many researches has been proposed to settle the SHO overhead by changing the SHO algorithm or the setting.

We use the way as [18] to model the sectorization. It use the way like brute force. Figure 1-10 would make it easier to show how we model the problem.

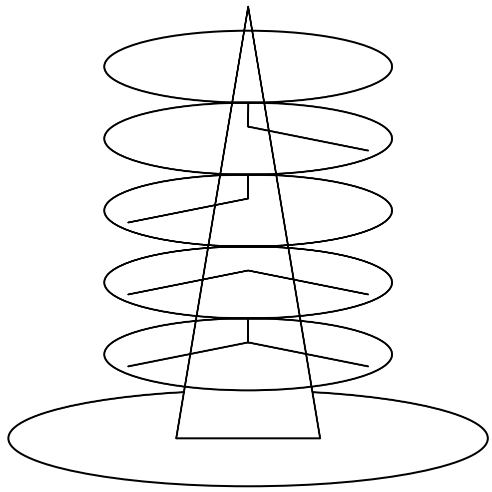


Figure 1-10 model sector

Imaging all kinds of sectors combined in a base station, with Lagrangian Relaxation, we could calculate the priority of all kinds of sectors of a base station, and use the result to set the sector.

### 1.2.7 Lagrangian Relaxation

Lagrangian methods were widely used in scheduling and the general integer programming problems in the 1970s**[8]** . Lagrangian relaxation can provide the proper solutions for those problems. Lagrangian relaxation has several advantages, for example, Lagrangian relaxation could let us decompose mathematical models in many different ways, so it is a flexible solution approach. Besides, Lagrangian relaxation solves the subproblems that we have decomposed as stand-alone problems. In fact, it has become one of the best tools for optimization problems such as integer programming, linear programming combinatorial optimization, and non-linear programming. Form now on, we can optimally solve the subproblems using any proper algorithm [1] [9] .

Lagrangian relaxation permits us to find out the boundary of our objective function, we can use it to implement heuristic solution for getting feasible solutions. Lagrangian relaxation is a flexible solution strategy that permits modelers to exploit the underlying structure in any optimization problem by relaxing complicating constraints. This method permits us to "pull apart" models by removing constraints and instead place them in the objective function with associated Lagrangian multipliers. The optimal value of the relaxed problem is always a lower bound (for minimization problems) on the objective function value of the problem. To obtain the best lower bound, we need to choose the minimization multiplier so that the optimal value of the Lagrangian subproblem is as large as possible. We can solve the Lagrangian multiplier problem in a variety of ways. The subgradient optimization technique is possibly the most popular technique for solving the Lagrangian multipliers problem [1] [9] .

## 1.3 Proposed Approach

We model the WCDMA base station deployment problem as a linear integer mathematical programming problem. In this optimization problem, we maximize the total revenue and get the suitable frequency assignment for system operator subject to QoS (SIR) constraint, power (capacity) constraint.

We will apply the Lagrangian relaxation method and the subgradient method to solve the problems.

# Chapter 2 Problem Formulation

## 2.1 Problem Description

In WCDMA system, the frequency reuse factor is 1 and the same frequency band is shared by all users, and is reused in each cell. Because the operator would get more than 5MHz, we add the frequency allocation problem considered in GSM system into this thesis as well. The amount of interference, delivered cell capacity, and total transmission power must be calculated.

We can decompose this big problem into following issues:

1. Base Station Allocation Issue: to allocate the base stations on the candidate locations to minimize the total cost and maximize the user profit.
2. Power Control Issue: to decide the transmission power and received power of each base station.
3. Sectorization Issue: to determine the sector configuration of each base station.
4. Homing Issue: to make each mobile terminal connect to the low loading base station or take off the mobile connection if the deployment cost larger than the users profits.
5. FDMA Issue: to decide the frequency assignment to each cell.

In WCDMA, uplink and downlink communications in wireless communication systems use two divided spectrums and we divide the problem in both directions.

The problem considered in this thesis is summarized below:

Table 2-1 Problem Description

- Objective: To plan the WCDMA base station placement considering maxima revenue.
- Assumptions:
  - A mobile terminal could be assigned to the lower loaded base station.
  - Code assignment is not considered (Orthogonal code resource is infinite).
  - Mobility is not considered.
  - The cost of each candidate place and the profit of each type of user are known.
  - Global information of all base stations and all mobile terminals is known
- Subject to:
  - QoS constraints.
  - Transmission power constraints
- Determine:
  - Base Station Allocation
  - Sectorization Configuration
  - Power Control
  - Connections
  - Frequency Assignment

## 2.2 Notation

Table 2-2 Notations of Given Parameters

| **Given Parameters** | |
|---|---|
| **Notation** | **Descriptions** |
| $B$ | The set of base stations |
| $B^j$ | The set of base stations which could be connected by MS *j*. |
| $T$ | The set of traffic types.(In our model, there are two kinds of rates) |
| $M$ | The set of mobile terminals. (In our model, there are two sets $M^t, t \in T$ ) |
| $M^t$ | The set of mobile terminals whose data rate are *t*. |
| $M^{tis_{kn}}$ | The set of mobile terminals whose data rate are *t* and could connect to the sector $s_{kn}$ of base station *i* |
| $S$ | The set of type of antenna. $s_{mn}$ means $m^{th}$ configuration and $n^{th}$ sector. |
| $K$ | The set of configuration of base stations. (In our simulation, the configuration of each base station including omni-directional antenna, two-sector antenna, and three-sector antenna.) |
| $R$ | The set of data rates. (In our simulation, there are two kinks of rates, voice and data) $R^r$ indicates the $r^{th}$ data rate of the data types. |
| $\Delta$ | The set of the bandwidth numbers |
| $BN$ | The number of $\Delta$ set. |
| $\Delta'$ | The set of the bandwidth numbers. The set is $\Delta$ plus 0 and BN. |
| $W^u$ | WCDMA chip rate in uplink |

| | |
|---|---|
| $W$ | WCDMA chip rate in downlink |
| $C_i^B$ | The cost of the BS locates in *i*. |
| $C_k^K$ | The cost of the additional cost to build antenna k |
| $D_{ij}$ | Distance between BS *i* and MS *j* |
| $D_{ii'}$ | Distance between BS *i* and BS *i'* |
| $Lp_{ij}^{\tau}$ | Path loss between BS *i* and MS *j* |
| $Lp_{ii'}^{\tau}$ | Path loss between BS *i* and BS *i'* |
| $R^t$ | The data bit rate of data rate *t*, $R^t \in R$ |
| $(\rho_{UL})^t$ | The $E_b / N_0$ requirement for transmission type *t* in the uplink |
| $(\rho_{DL})^t$ | The requirement for transmission type *t* in the downlink |
| $v^t$ | Activity factor of data type t |
| $P_N$ | Thermal noise strength |
| $P_{BS}$ | Maximum total transmission power of a base station |
| $P_{MS}$ | Maximum total transmission power of a mobile station |
| $\lambda$ | Wave length |
| $\tau$ | Attenuation factor |
| $\alpha$ | Orthogonality factor of mobile terminal in the downlink |
| $H$ | A arbitrary large number |
| $\mu_{is_{kn}j}$ | Indicator function which is 1 if mobile terminal *j* can be served by antenna $s_{kn}$ in base station *i* and 0 otherwise. |
| $\phi_{is_{kn}0}, \phi_{is_{kn}(BN+1)}$ | Two artificial numbers which are both always 0. |
| $pf^t$ | The profit from data type *t*. |

Table 2-3 Notations of Decision Variables

| **Decision Variables** | |
|---|---|
| **Notation** | **Descriptions** |
| $l_i$ | Decision variable which is 1 if BS *i* is selected to build, 0 otherwise. |
| $a_{ik}$ | Decision variable which is 1 if base station *i* uses $k^{th}$ configuration. |
| $x_{jis_{kn}}$ | Decision variable which is 1 if mobile terminal *j* is served by antennas $s_{kn}$ of base station *i* in uplink and 0 otherwise. |
| $p^t_{is_{kn}}$ | The required received power of sector $s_{kn}$ of base station $i$ . The power could. |
| $q_{is_{kn}j}$ | Total transmission power of sector $s_{kn}$ of base station *i* to mobile *j*. The power could be 0 or a number larger than S. |
| $\phi_{is_{kn}b}$ | Decision variable which is 1 if the sector $s_{kn}$ of base station *i* take the bandwidth *b* |
| $y_{is_{kn}i's_{kn}'b}$ | Decision variable which is 1 if the sector $s_{kn}$ of base station *i* believes the sector $s_{k'n'}$ of base station *i'* uses the same bandwidth *b*. |

## 2.3 Problem Formulation

**Optimization problem (IP1):**

Objective function:

| | |
|---|---|
| $Min\sum_{i\in B}\left(l_i * C_i^B + \sum_{k\in K} a_{ik} * C_k^K\right) - \sum_{t\in T}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{j\in M} x_{ji's_{k'n'}} * pf^t$ | (IP1) |

subject to:

| | | |
|---|---|---|
| $\left(\rho_{UL}\right)^t \le \dfrac{p^t_{is_{kn}} \dfrac{W^u}{\left(R_{UL}\right)^t}}{P_N + \sum_{o\in T}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{e\in M^{ti's_{k'n'}}} p^o_{i's_{k'n'}} v^o x_{ei's_{k'n'}} * \mu_{is_{kn}e} \dfrac{Lp^{\tau}_{i'e}}{Lp^{\tau}_{ie}} - p^t_{is_{kn}}}$ | $\forall t \in T$, $\forall i \in B$, $\forall s_{kn} \in S$ | (2.1) |
| $p^t_{is_{kn}} * x_{jis_{kn}} * Lp^{\tau}_{ij} \le P_{MS}$ | $\forall t \in T$ $\forall i \in B$ $\forall s_{kn} \in S$ $\forall j \in M^{tis_{kn}}$ | (2.2) |
| $x_{jis_{kn}} = 0 \text{ or } 1$ | $\forall i \in B^j$ $\forall s_{kn} \in S$ $\forall j \in M^{tis_{kn}}$ | (2.3) |
| $\sum_{i\in B^j}\sum_{s_{kn}\in S} x_{jis_{kn}} \le 1$ | $\forall t \in T$ $\forall j \in M^t$ | (2.4) |
| $x_{jis_{kn}} \le u_{is_{kn}j}$ | $\forall t \in T$ $\forall i \in B$ $\forall s_{kn} \in S$ $\forall j \in M^t$ | (2.5) |
| $x_{jis_{kn}} \le q_{is_{kn}j}$ | $\forall t \in T$ $\forall i \in B$ $\forall s_{kn} \in S$ $\forall j \in M^{tis_{kn}}$ | (2.6) |
| $q_{is_{kn}j} \le x_{jis_{kn}} * H$ | $\forall t \in T$ $\forall i \in B$ $\forall s_{kn} \in S$ $\forall j \in M^{tis_{kn}}$ | (2.7) |

| | | |
|---|---|---|
| $(\rho_{DL})^t \le \dfrac{\dfrac{q_{is_{kn}j}}{Lp_{ij}^{\tau}} * \dfrac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{(R_{DL})^t(BN)} + \left(1 - x_{jis_{kn}}\right) * epsilon}{\left[\begin{array}{l} 10^{-13.4} * \sum_{f\in\Delta}\phi_{is_{kn}f} * \dfrac{W}{BN} \\ + (1-\alpha)\left(\sum_{q\in T}\sum_{j'\in M^{qis_{kn}}, j'\neq j}\dfrac{q_{is_{kn}j'} * v^q}{Lp_{ij}^{\tau}}\right) \\ \qquad \dfrac{\left(\sum_{r\in T}\sum_{m\in M^{ri's_{k'n'}}} q_{i's_{k'n'}m} * v^r\right) * \mu_{i's_{k'n'}j}}{Lp_{i'j}^{\tau}} \\ + \sum_{i'\in B}\sum_{s_{k'n'}\in S} * \dfrac{\sum_{c\in\Delta} y_{is_{kn}i's_{k'n'}c}}{\sum_{d\in\Delta}\phi_{i's_{k'n'}d}} \\ - \sum_{\theta\in T}\sum_{j''\in M^{\theta is_{kn}}}\dfrac{q_{is_{kn}j''} * v^{\theta}}{Lp_{ij}^{\tau}} \end{array}\right]}$ | $\forall t\in T$<br>$\forall i\in B$<br>$\forall s_{kn}\in S$<br>$\forall j\in M^{tis_{kn}}$ | (2.8) |
| $\phi_{is_{kn}b} = 0 \text{ or } 1$ | $\forall i\in B$<br>$\forall s_{kn}\in S$<br>$\forall b\in\Delta$ | (2.9) |
| $\sum_{b=1}^{BN+1}\left(\phi_{is_{kn}b} - \phi_{is_{kn}b-1}\right)^2 = 2$ | $\forall i\in B$<br>$\forall s_{kn}\in S$ | (2.10) |
| $y_{is_{kn}i's_{k'n'}b} \le \phi_{is_{kn}b}$ | $\forall i\in B$<br>$\forall s_{kn}\in S$<br>$\forall i'\in B$<br>$\forall s_{k'n'}\in S$<br>$\forall b\in\Delta$ | (2.11) |
| $y_{is_{kn}i's_{k'n'}b} \le \phi_{i's_{k'n'}b}$ | $\forall i\in B$<br>$\forall s_{kn}\in S$<br>$\forall i'\in B$<br>$\forall s_{k'n'}\in S$<br>$\forall b\in\Delta$ | (2.12) |
| $y_{is_{kn}i's_{kn}'b} \ge \dfrac{\phi_{is_{kn}b} + \phi_{i's_{k'n'}b} - 1}{2}$ | $\forall i\in B$<br>$\forall s_{kn}\in S$<br>$\forall i'\in B$<br>$\forall s_{k'n'}\in S$<br>$\forall b\in\Delta$ | (2.13) |

| | | |
|---|---|---|
| $y_{is_{kn}i's_{k'n'}b} =$ 0 or 1 | $\forall i \in B$<br>$\forall s_{kn} \in S$<br>$\forall i' \in B$<br>$\forall s_{k'n'} \in S$<br>$\forall b \in \Delta$ | (2.14) |
| $\sum_{t \in T} \sum_{j \in M^{tis_{kn}}} q_{is_{kn}j} \le P_{BS}$ | $\forall i \in B$<br>$\forall s_{kn} \in S$ | (2.15) |
| $l_i = 0$ or 1 | $\forall i \in B$ | (2.16) |
| $a_{ik} = 0$ or 1 | $\forall i \in B,$<br>$k \in K$ | (2.17) |
| $q_{is_{kn}j} \le a_{ik} * H$ | $\forall t \in T$<br>$\forall i \in B$<br>$\forall k \in K$<br>$\forall s_{kn} \in S$<br>$\forall j \in M^{tis_{kn}}$ | (2.18) |
| $x_{jis_{kn}} \le a_{ik}$ | $\forall t \in T$<br>$\forall i \in B$<br>$\forall k \in K$<br>$\forall s_{kn} \in S$<br>$\forall j \in M^{tis_{kn}}$ | (2.19) |
| $\sum_{k \in K} a_{ik} = l_i$ | $\forall i \in B$ | (2.20) |
| $q_{is_{kn}j} \le \mu_{is_{kn}j} * H$ | $\forall t \in T$<br>$\forall j \in M^{t}$<br>$\forall i \in B$<br>$\forall s_{kn} \in S$ | (2.21) |

The objective function of (IP1) is to maximize the total revenue calculated by subtracting the deployment costs from total users' profits. In terms of convenience, we can translate the problem into an equivalent description that is to minimize the negative system total revenue.

The set of constraints is explained bellow.

**1) Uplink QoS and power constraints:**

This set includes constraints (2.1), (2.2), (2.3), (2.4) (2.5). Each admitted mobile station should hold its uplink SIR (QoS) constraint and its maximum power constraint.

Constraint (2.1) ensures the uplink QoS. It requires the received power of base station *i* divided by sum of received power from all other mobile station plus background noise power larger than the uplink SIR requirement. Constraint (2.2) ensures the transmission power of mobile station *j* not exceeding its maximum power if it connected to the base station. Constraint (2.3) ensures the connection variable is 0 or 1. Constraint (2.4) ensures the total connection of a mobile station is less than 1. Constraint (2.5) ensures the connection in the sector coverage.

**2) Downlink QoS, power constraints and FDMA constraints**

This set includes constraints (2.8), (2.9), (2.10), (2.11), (2.12), (2.13), (2.14), (2.15), (2.21) and (2.22). Each admitted mobile station should hold its downlink SIR (QoS) constraint and all base stations' maximum power constraint and FDMA constraints. Constraint (2.8) ensures the sum of SIR been satisfied. It requires the received power strength of mobile station *j* divided by total power from other base stations plus background noise larger than its downlink SIR requirement if it has connection to base station. Constraint (2.15) ensures the total power transmitted from a base station not larger than the power limitation. Constraint (2.21) ensures the power transmitted from the base station to the mobile stations in its coverage. Constraints (2.9) to (2.13) ensure the FDMA requirements. '*y*' is an artificial surplus decision variable in order to present the relationship between the same frequency of two base stations. The existence of '*y*' could reduce the complex of the problem for dismiss the multiplication of $\phi_{is_{kn}b}$ and $\phi_{i's_{k'n'}b}$. If the two base stations use the same frequency, '*y*' should be 1 and 0 otherwise. Constraints (2.9) and (2.10) ensure the used frequencies been serial and the frequency is discrete. Constraints (2.11), (2.12), (2.13) and (2.14) ensure the decision variable '*y*' equals the multiplication of $\phi_{is_{kn}b}$ and $\phi_{i's_{k'n'}b}$.

**3) Deployment constraints**

This set includes constraints (2.16), (2.17) and (2.20). (2.16) and (2.17) ensures the deployment or the sectorization configuration is built or not. (2.20) ensures the place where built a base station select just one sectorization configuration.

**4) Relationships between uplink, downlink and deployment constraints**

This set includes constraints (2.6), (2.7), (2.18) and (2.19). Constraints (2.6) and (2.7) present that if the connection between a mobile station and a base station is set up, the mobile must receive a signal power from the base station. If a base station sent a signal power to a mobile, there must be a connection.

Constraints (2.18) and (2.19) ensure the connections and the powers only been set when the sectorization configuration is selected.

# Chapter 3 Solution Approach

## 3.1 Lagrangian Relaxation

As conventional, we transform the maximization problem to minimization without loss of correctness. By using the Lagrangian relaxation method, the primal problem (IP1) can be transform in the following Lagrangian relaxation problem (LR) where constraints (2.1), (2.4), (2.6), (2.7), (2.8), (2.11), (2.13), (2.18) and (2.19) are relaxed. For a vector of non-negative Lagrangian multipliers, a Lagrangian relaxation problem of IP1 is given by an optimization problem (LR) as below:

**Optimization Problem (LR):**

$$\min \sum_{i\in B}\left(l_i * C_i^B + \sum_{k\in K} a_{ik} * C_k^K\right) - \sum_{t}\sum_{i'}\sum_{k'}\sum_{n'}\sum_{j\in M^{ti's_{k'n'}}} x_{ji's_{k'n'}} * pf^t$$

$$+\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S} u^1_{tis_{kn}} \left\{ (\rho_{UL})^t \left( P_N + \sum_{o\in T}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{e\in M^{ti's_{k'n'}}} p^o_{i's_{k'n'}} v^o x_{ei's_{k'n'}} * \mu_{is_{kn}e} \frac{Lp^\tau_{i'e}}{Lp^\tau_{ie}} - p^t_{is_{kn}} \right) - p^t_{is_{kn}} \frac{W^u}{(R_{UL})^t} \right\}$$

$$+\sum_{t\in T}\sum_{j\in M^t} u^2_{tj}\left(\sum_{i\in B^j}\sum_{s_{kn}\in S} x_{jis_{kn}} - 1\right)$$

$$+\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^3_{tis_{kn}j}\left(x_{jis_{kn}} - q_{is_{kn}j}\right)$$

$$+\sum_{t\in T}\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^4_{tis_{kn}jk}\left(x_{jis_{kn}} - a_{ik}\right)$$

$$+\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^5_{tis_{kn}j} \left( \begin{array}{l} (\rho_{DL})^t \left\{ \begin{array}{l} 10^{-13.4} * \sum_{f\in\Delta}\phi_{is_{kn}f} * \frac{W}{BN} \\ +(1-\alpha)\left(\sum_{q\in T}\sum_{j'\in M^{qis_{kn}}, j'\neq j} \frac{q_{is_{kn}j'} * v^q}{Lp^\tau_{ij}}\right) \\ +\sum_{i'\in B}\sum_{s_{k'n'}\in S} \frac{\sum_{r\in T}\sum_{m\in M^{ri's_{k'n'}}} q_{i's_{k'n'}m} * v^r * \mu_{i's_{k'n'}j}}{Lp^\tau_{i'j}} * \frac{\sum_{c\in\Delta} y_{is_{kn}i's_{kn}'c}}{\sum_{d\in\Delta}\phi_{i's_{k'n'}d}} \\ -\sum_{\theta\in T}\sum_{j''\in M^{\theta is_{kn}}} \frac{q_{is_{kn}j''} * v^\theta}{Lp^\tau_{ij}} \end{array}\right\} \\ -\left[\left(\frac{q_{is_{kn}j}}{Lp^\tau_{ij}} * \frac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{(R_{DL})^t (BN)}\right) + \left(1 - x_{jis_{kn}}\right) * H\right] \end{array}\right)$$

$$+\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^6_{tis_{kn}j}\left(q_{is_{kn}j} - x_{jis_{kn}} * H\right)$$

$$+\sum_{t\in T}\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^7_{tis_{kn}jk}\left(q_{is_{kn}j} - \left(a_{ik} * H\right)\right)$$

$$+\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta} u^8_{is_{kn}i's_{k'n'}b}\left(y_{is_{kn}i's_{k'n'}b} - \phi_{is_{kn}b}\right)$$

$$+\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta} u^9_{is_{kn}i's_{k'n'}b}\left(\phi_{is_{kn}b} + \phi_{i's_{k'n'}b} - 1 - 2y_{is_{kn}i's_{k'n'}b}\right)$$

Subject to:

| | | |
|---|---|---|
| $x_{jis_{kn}} \le u_{is_{kn}j}$ | $\forall t \in T,\ \forall i \in B$<br>$\forall s_{kn} \in S,\ \forall j \in M^t$ | (3.1) |
| $x_{jis_{kn}} = 0$ or $1$ | $\forall i \in B^j, \forall s_{kn} \in S, \forall j \in M^{tis_{kn}}$ | (3.2) |
| $p^t_{is_{kn}} * x_{jis_{kn}} * Lp^\tau_{ij} \le P_{MS}$ | $\forall t \in T,\ \forall i \in B$<br>$\forall s_{kn} \in S,\ \forall j \in M^{tis_{kn}}$ | (3.3) |

| | | |
|---|---|---|
| $q_{is_{kn}j} \le \mu_{is_{kn}j} * H$ | $\forall t \in T,\ \forall j \in M^t$<br>$\forall i \in B,\ s_{kn} \in S$ | (3.4) |
| $\sum_{t \in T} \sum_{j \in M^{tis_{kn}}} q_{is_{kn}j} \le P_{BS}$ | $\forall i \in B,\ \forall s_{kn} \in S$ | (3.5) |
| $\phi_{is_{kn}b} = 0$ or 1 | $\forall i \in B$<br>$\forall s_{kn} \in S$<br>$\forall b \in \Delta$ | (3.6) |
| $\sum_{b=1}^{BN+1} \left(\phi_{is_{kn}b} - \phi_{is_{kn}b-1}\right)^2 = 2$ | $\forall i \in B$<br>$\forall s_{kn} \in S$ | (3.7) |
| $y_{is_{kn}i's_{k'n'}b} \le \phi_{i's_{k'n'}b}$ | $\forall i' \in B,\ \forall s_{k'n'} \in S$<br>$\forall i \in B,\ \forall s_{kn} \in S,\ \forall b \in \Delta$ | (3.8) |
| $y_{is_{kn}i's_{k'n'}b} =$ 0 or 1 | $\forall i \in B,\ \forall s_{kn} \in S$<br>$\forall i' \in B,\ \forall s_{k'n'} \in S,\ \forall b \in \Delta$ | (3.9) |
| $l_i = 0$ or 1 | $\forall i \in B$ | (3.10) |
| $a_{ik} = 0$ or 1 | $\forall i \in B,\ k \in K$ | (3.11) |
| $\sum_{k \in K} a_{ik} = l_i$ | $\forall i \in B$ | (3.12) |

where $u^1, u^2, u^3, u^4, u^5, u^6, u^7, u^8$ and $u^9$ are the vectors of non-negative Lagrangian multipliers $\{u^1_{tis_{kn}}\}, \{u^2_{tj}\}, \{u^3_{tis_{kn}j}\}, \{u^4_{tis_{kn}jk}\}, \{u^5_{tis_{kn}j}\}, \{u^6_{tis_{kn}j}\}, \{u^7_{tis_{kn}jk}\}, \{u^8_{is_{kn}i's_{k'n'}b}\}$ and $\{u^9_{is_{kn}i's_{k'n'}b}\}$. To solve (LR), we decompose the problem into the following three independent optimization subproblems.

### 3.1.1 Subproblem 1 (related to decision variables $p_{is_{kn}}^{t}$, $x_{jis_{kn}}$)

$$
\begin{aligned}
& \min \\
& \left[ \begin{aligned}
& \sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S} u_{tis_{kn}}^{1}\left(\rho_{UL}\right)^{t} P_{N} \\
& +\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S} u_{tis_{kn}}^{1}\left(\rho_{UL}\right)^{t} \sum_{o\in T}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{e\in M^{oi's_{k'n'}}} p_{i's_{k'n'}}^{o} v^{o} x_{ei's_{k'n'}} * \mu_{is_{kn}e} \frac{Lp_{i'e}^{\tau}}{Lp_{ie}^{\tau}} \\
& -\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S} u_{tis_{kn}}^{1}\left(\rho_{UL}\right)^{t} p_{is_{kn}}^{t} - \sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S} u_{tis_{kn}}^{1} p_{is_{kn}}^{t} \frac{W^{u}}{\left(R_{UL}\right)^{t}}
\end{aligned} \right] \\
& +\sum_{t\in T}\sum_{j\in M^{t}} u_{tj}^{2}\left(\sum_{i\in B^{j}}\sum_{s_{kn}\in S} x_{jis_{kn}} - 1\right) \\
& +\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u_{tis_{kn}j}^{3} x_{jis_{kn}} \\
& +\sum_{t\in T}\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u_{tis_{kn}jk}^{4} x_{jis_{kn}} \\
& -\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u_{tis_{kn}j}^{5}\left(1-x_{jis_{kn}}\right) * epsilon - \sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u_{tis_{kn}j}^{6} * x_{jis_{kn}} * H \\
& -\sum_{t}\sum_{i'}\sum_{k'}\sum_{n'}\sum_{j\in M^{ti's_{k'n'}}} x_{ji's_{k'n'}} * pf^{t}
\end{aligned}
$$

Subject to:

| | | |
|---|---|---|
| $x_{jis_{kn}} \le u_{is_{kn}j}$ | $\forall t\in T,\ \forall i\in B$ <br> $\forall s_{kn}\in S,\ \forall j\in M^{t}$ | (3.1) |
| $x_{jis_{kn}} = 0$ or 1 | $\forall i\in B^{j}, \forall s_{kn}\in S, \forall j\in M^{tis_{kn}}$ | (3.2) |
| $p_{is_{kn}}^{t} * x_{jis_{kn}} * Lp_{ij}^{\tau} \le P_{MS}$ | $\forall t\in T,\ \forall i\in B$ <br> $\forall s_{kn}\in S,\ \forall j\in M^{tis_{kn}}$ | (3.3) |

To rewrite SUB 3.1, we can get

*min*

$$\sum_{t\in T}\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\left[\begin{array}{l} +\sum_{j\in M^{tis_{kn}}} x_{jis_{kn}} \left[\begin{array}{l} p^t_{is_{kn}} v^t \sum_{o\in T}\sum_{i'\in B}\sum_{s_{k'n'}\in S} u^1_{oi's_{k'n'}} \left(\rho_{UL}\right)^0 * \mu_{i's_{k'n'}j} \frac{Lp^{\tau}_{ij}}{Lp^{\tau}_{i'j}} \\ +u^2_{tj} + u^3_{tis_{kn}j} + u^4_{tis_{kn}jk} \\ +u^5_{tis_{kn}j} * epsilon - u^6_{tis_{kn}j} * H - pf^t \\ \end{array}\right] \\ -u^1_{tis_{kn}} p^t_{is_{kn}} \left[\left(\rho_{UL}\right)^t + \frac{W^u}{\left(R_{UL}\right)^t}\right] \end{array}\right]$$

$$+\sum_{t\in T}\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S} u^1_{tis_{kn}} \left(\rho_{UL}\right)^t P_N$$

$$-\sum_{t\in T}\sum_{j\in M^t} u^2_{tj} - \sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^5_{tis_{kn}j} * epsilon$$

According to constraints (3.1), we could change the formula $\sum_{j\in M^t}\sum_{i\in B^j}\sum_{s_{kn}\in S} x_{jis_{kn}}$ to $\sum_{i\in B^j}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} x_{jis_{kn}}$ because the connection for mobile *j* to the sector of base station *i* would be 0 if it is not in the coverage. Base the formula above, we could solve this subproblem by setting $indicator[|M|] = \left[\begin{array}{l} p^t_{is_{kn}} v^t \sum_{o\in T}\sum_{i'\in B}\sum_{s_{k'n'}\in S} u^1_{oi's_{k'n'}} \left(\rho_{UL}\right)^0 * \mu_{i's_{k'n'}j} \frac{Lp^{\tau}_{ij}}{Lp^{\tau}_{i'j}} \\ +u^2_{tj} + u^3_{tis_{kn}j} + u^4_{tis_{kn}jk} \\ +u^5_{tis_{kn}j} * epsilon - u^6_{tis_{kn}j} * H - pf^t \\ \end{array}\right]$. Let decision variable $p^t_{is_{kn}}$ discrete and we could exhaustively search all possible value of $p^t_{is_{kn}}$ and get an indicator value. If indicator < 0, we let decision variable *x* 1, or 0 otherwise.

### 3.1.2 Subproblem 2 (related to decision variables $q_{is_{kn}j}, \phi_{is_{kn}b}, y_{is_{kn}i's_{k'n'}b}$)

min

$$
\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^{5}_{tis_{kn}j}
\left(
(\rho_{DL})^{t}
\left\{
\begin{array}{l}
10^{-13.4} * \sum_{f\in\Delta}\phi_{is_{kn}f} * \frac{W}{BN} \\
+(1-\alpha)\left(\sum_{q\in T}\sum_{j'\in M^{qis_{kn}}, j'\neq j}\frac{q_{is_{kn}j'} * v^{q}}{Lp^{\tau}_{ij}}\right) \\
+\sum_{i'\in B}\sum_{s_{k'n'}\in S}\left(\frac{\left(\sum_{r\in T}\sum_{m\in M^{ri's_{k'n'}}} q_{i's_{k'n'}m} * v^{r} * \mu_{i's_{k'n'}j}\right)}{Lp^{\tau}_{i'j}} * \frac{\sum_{c\in\Delta} y_{is_{kn}i's_{kn}'c}}{\sum_{d\in\Delta}\phi_{i's_{k'n'}d}}\right) \\
-\sum_{\theta\in T}\sum_{j''\in M^{\theta is_{kn}}}\frac{q_{is_{kn}j''} * v^{\theta}}{Lp^{\tau}_{ij}}
\end{array}
\right\}
-\frac{q_{is_{kn}j}}{Lp^{\tau}_{ij}} * \frac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{(R_{DL})^{t}(BN)}
\right)
$$

$$
+\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^{6}_{tis_{kn}j} * q_{is_{kn}j}
$$

$$
+\sum_{t\in T}\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^{7}_{tis_{kn}jk} q_{is_{kn}j}
$$

$$
+\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta} u^{8}_{is_{kn}i's_{k'n'}b}\left(y_{is_{kn}i's_{kn}'b} - \phi_{is_{kn}b}\right)
$$

$$
+\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta} u^{9}_{is_{kn}i's_{k'n'}b}\left(\phi_{is_{kn}b} + \phi_{i's_{kn}'b} - 1 - 2y_{is_{kn}i's_{kn}'b}\right)
$$

$$
-\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^{3}_{tis_{kn}j} * q_{is_{kn}j}
$$

Subject to:

| | | |
|---|---|---|
| $q_{is_{kn}j} \leq \mu_{is_{kn}j} * H$ | $\forall t\in T,\ \forall j\in M^{t}$<br>$\forall i\in B,\ s_{kn}\in S$ | (3.4) |
| $\sum_{t\in T}\sum_{j\in M^{tis_{kn}}} q_{is_{kn}j} \leq P_{BS}$ | $\forall i\in B,\ \forall s_{kn}\in S$ | (3.5) |
| $\phi_{is_{kn}b} = 0$ or 1 | $\forall i\in B$<br>$\forall s_{kn}\in S$<br>$\forall b\in\Delta$ | (3.6) |

| | | |
|---|---|---|
| $\sum_{b=1}^{BN+1}\left(\phi_{is_{kn}b}-\phi_{is_{kn}b-1}\right)^2=2$ | $\forall i\in B$<br>$\forall s_{kn}\in S$ | (3.7) |
| $y_{is_{kn}i's_{k'n'}b}\le \phi_{i's_{k'n'}b}$ | $\forall i'\in B,\ \forall s_{k'n'}\in S$<br>$\forall i\in B,\ \forall s_{kn}\in S,\ \forall b\in\Delta$ | (3.8) |
| $y_{is_{kn}i's_{k'n'}b}=$ 0 or 1 | $\forall i\in B,\ \forall s_{kn}\in S$<br>$\forall i'\in B,\ \forall s_{k'n'}\in S,\ \forall b\in\Delta$ | (3.9) |

To rewrite SUB 3.2, we can get

$$
\begin{aligned}
=\min \\
\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}
&\left(
\begin{aligned}
&\sum_{t\in T}\sum_{j\in M^{tis_{kn}}} u^5_{tis_{kn}j} *\left(\rho_{DL}\right)^t * 10^{-13.4} * \sum_{f\in\Delta}\phi_{is_{kn}f} * \frac{W}{BN} \\
&-\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta}\phi_{is_{kn}b}\left(u^8_{is_{kn}i's_{k'n'}b}-u^9_{is_{kn}i's_{k'n'}b}-u^9_{i's_{k'n'}is_{kn}b}\right) \\
&-\sum_{t\in T}\sum_{j\in M^{tis_{kn}}} q_{is_{kn}j}
\left(
\begin{aligned}
&\left[
\begin{aligned}
&\sum_{q\in T}\sum_{j'\in M^{qis_{kn}}}\left(\rho_{DL}\right)^q\left(\alpha u^5_{qis_{kn}j'}\frac{v^t}{Lp^{\tau}_{ij'}}\right) \\
&+u^5_{tis_{kn}j} *\left(\rho_{DL}\right)^t\left(1-\alpha\right)\frac{v^t}{Lp^{\tau}_{ij}} \\
&+\frac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{Lp^{\tau}_{ij}\left(R_{DL}\right)^t\left(BN\right)}u^5_{tis_{kn}j}
\end{aligned}
\right] \\
&-u^6_{tis_{kn}j}-u^7_{tis_{kn}jk}+u^3_{tis_{kn}j}
\end{aligned}
\right) \\
&+\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta} y_{i's_{k'n'}is_{kn}b}
\left(
\begin{aligned}
&\frac{\sum_{r\in T}\sum_{m\in M^{ris_{kn}}} q_{is_{kn}m} * v^r}{\sum_{d\in\Delta}\phi_{is_{kn}d}} \\
&*\sum_{t\in T}\sum_{j\in M^{ti's_{k'n'}}}\frac{\left(\rho_{DL}\right)^t\left(\mu_{is_{kn}j}\right)u^5_{ti's_{k'n'}j}}{Lp^{\tau}_{ij}} \\
&+u^8_{i's_{k'n'}is_{kn}b}-2u^9_{i's_{k'n'}is_{kn}b}
\end{aligned}
\right)
\end{aligned}
\right) \\
-\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta} u^9_{is_{kn}i's_{k'n'}b}
\end{aligned}
$$

It is a complex subproblem and there are four steps to solve the problem.

1. Use exhaustive search to determine all kinds of “summation frequency” configuration.

When determine one configuration, calculate the value of $-\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta}\phi_{is_{kn}b}\left(u^{8}_{is_{kn}i's_{k'n'}b}-u^{9}_{is_{kn}i's_{k'n'}b}-u^{9}_{i's_{k'n'}is_{kn}b}\right)$, use exhaustive search to find the minimize value of all composing of summation frequency. We could reduce the complexity of this subproblem by this way.

2. After determine the frequency configuration, calculate all $indicator[|M|]$ = $\left[\begin{array}{l}\sum_{q\in T}\sum_{j'\in M^{qis_{kn}}}\left(\rho_{DL}\right)^{q}\left(\alpha u^{5}_{qis_{kn}j'}\dfrac{v^{t}}{Lp^{\tau}_{ij'}}\right)\\ +u^{5}_{tis_{kn}j}*\left(\rho_{DL}\right)^{t}(1-\alpha)\dfrac{v^{t}}{Lp^{\tau}_{ij}}\\ +\dfrac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{Lp^{\tau}_{ij}\left(R_{DL}\right)^{t}(BN)}u^{5}_{tis_{kn}j}\end{array}\right]$ $-u^{6}_{tis_{kn}j}-u^{7}_{tis_{kn}jk}+u^{3}_{tis_{kn}j}$ and make transmit power $q_{is_{kn}j}$ be discrete. Since we could arrange $indicator[|M|]$ from large to small until the indicator value<0 or we exhaust all power then the sort algorithm could be stopped.

3. Still, we have to determine total transmit power $\dfrac{\sum_{r\in T}\sum_{m\in M^{ris_{kn}}}q_{is_{kn}m}*v^{r}}{\sum_{d\in\Delta}\phi_{is_{kn}d}}$ to determine the value of decision variables $y$. Because the total transmit power here is better less. By exhaustively searching the total transmit power which is formed from step 2 and the indicator value should be larger than 0, we could determine the values of $y_{i's_{k'n'}is_{kn}b}$ from the $indicator2[|B|*|S|*|BN|]$ = $\left(\begin{array}{l}\dfrac{\sum_{r\in T}\sum_{m\in M^{ris_{kn}}}q_{is_{kn}m}*v^{r}}{\sum_{d\in\Delta}\phi_{is_{kn}d}}\\ *\sum_{t\in T}\sum_{j\in M^{ti's_{k'n'}}}\dfrac{\left(\rho_{DL}\right)^{t}\left(\mu_{is_{kn}j}\right)u^{5}_{ti's_{k'n'}j}}{Lp^{\tau}_{ij}}\\ +u^{8}_{i's_{k'n'}is_{kn}b}-2u^{9}_{i's_{k'n'}is_{kn}b}\end{array}\right)$. If

indicator2<0, $y_{i's_{k'n'}is_{kn}b}$ should be 1 and 0 otherwise. Record the best result during the exhaustive search and find the best solution of total power and *y*.

4. Calculate the total value and compare the value with other frequency configurations. We could exhaustively get the minimum configuration.

### 3.1.3 Subproblem 3 (related to decision variables $l_i, a_{ik}$)

$$\min \sum_{i\in B}\left( l_i * C_i^B + \sum_{k\in K} a_{ik} * C_k^K \right)$$
$$-\sum_{t\in T}\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^4_{tis_{kn}jk} a_{ik}$$
$$-\sum_{t\in T}\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\sum_{j\in M^{is_{kn}j}} u^7_{tis_{kn}jk} a_{ik} * H$$

Subject to:

| | | |
|---|---|---|
| $l_i = 0$ or 1 | $\forall i \in B$ | (3.10) |
| $a_{ik} = 0$ or 1 | $\forall i \in B,\ k \in K$ | (3.11) |
| $\sum a_{ik} = l_i$ | $\forall i \in B$ | (3.12) |

To rewrite SUB 3.3, we can get

$$= \min$$
$$\sum_{i\in B} l_i * C_i^B$$
$$+\sum_{i\in B}\sum_{k\in K} a_{ik}\left( C_k^K - \sum_{t\in T}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^4_{tis_{kn}jk} - H\sum_{t\in T}\sum_{s_{kn}\in S}\sum_{j\in M^{is_{kn}j}} u^7_{tis_{kn}jk} \right)$$

For each base station *i*, we could calculate all values of all kinds of configuration and exhaustively get the best one.

## 3.2 The Dual Problem and the Subgradient Method

According to the weak Lagrangian duality theorem, for any $u^1_{mit}, u^2_m, u^3_m, u^4_{mt}, u^5_{mi}, u^6_{mi} \ge 0$,

$Z_D\left(u^1_{mit}, u^2_m, u^3_m, u^4_{mt}, u^5_{mi}, u^6_{mi}\right)$ is a lower bound on $Z_{IP1}$. The following dual problem (D) is constructed to calculate the tightest lower bound.

**Dual Problem (D):**

$$Z_D = \max Z_D\left(u^1_{tis_{kn}}, u^2_{tj}, u^3_{tis_{kn}j}, u^4_{tis_{kn}jk}, u^5_{tis_{kn}j}, u^6_{tis_{kn}j}, u^7_{tis_{kn}jk}, u^8_{is_{kn}i's_{k'n'}b}, u^9_{is_{kn}i's_{k'n'}b}\right)$$

subject to:

$$u^1_{tis_{kn}}, u^2_{tj}, u^3_{tis_{kn}j}, u^4_{tis_{kn}jk}, u^5_{tis_{kn}j}, u^6_{tis_{kn}j}, u^7_{tis_{kn}jk}, u^8_{is_{kn}i's_{k'n'}b}, u^9_{is_{kn}i's_{k'n'}b} \geq 0$$

The most common method for solving the dual problem is the subgradient method. Let $g$ be a subgradient of $Z_D\left(u^1_{tis_{kn}}, u^2_{tj}, u^3_{tis_{kn}j}, u^4_{tis_{kn}jk}, u^5_{tis_{kn}j}, u^6_{tis_{kn}j}, u^7_{tis_{kn}jk}, u^8_{is_{kn}i's_{k'n'}b}, u^9_{is_{kn}i's_{k'n'}b}\right)$. Then, in iteration $k$ of the subgradient optimization procedure, the multiplier vector $\pi = \left(u^1_{tis_{kn}}, u^2_{tj}, u^3_{tis_{kn}j}, u^4_{tis_{kn}jk}, u^5_{tis_{kn}j}, u^6_{tis_{kn}j}, u^7_{tis_{kn}jk}, u^8_{is_{kn}i's_{k'n'}b}, u^9_{is_{kn}i's_{k'n'}b}\right)$ is updated by $\pi^{k+1} = \pi^k + t^k g^k$. The step size $t^k$ is determined by $t^k = \delta \frac{Z^h_{IP} - Z_D(\pi_k)}{\left\|g^k\right\|^2}$. $Z^h_{IP}$ is the primal objective function value for a heuristic solution and $\delta$ is constant between 0 and 2.

## 3.3 Model Extension and Modification

**Model Extension:**

We omit the effects of soft handoff in this thesis because the computation complexity. However, we provide the way to model the soft handoff of the SIR combination.

If we let the SIR in both uplink and downlink be decision variables, we could let the combination of SIR decision variables larger than the needed SIR. The model extension in downlink could be made as bellow.

| | | |
|---|---|---|
| $(\rho_{DL})_{is_{kn}j} + \varepsilon_1 \le \dfrac{\dfrac{q_{is_{kn}j}}{Lp_{ij}^{\tau}} * \dfrac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{(R_{DL})^{t}(BN)} + \varepsilon_2}{\left[10^{-13.4} * \sum_{f\in\Delta}\phi_{is_{kn}f} * \dfrac{W}{BN} + (1-\alpha)\left(\sum_{q\in T}\sum_{j'\in M^{tis_{kn}},\, j'\neq j}\dfrac{q_{is_{kn}j'} * v^{q}}{Lp_{ij}^{\tau}}\right) + \sum_{i'\in B}\sum_{s_{k'n'}\in S}\dfrac{\left(\sum_{r\in T}\sum_{m\in M^{ri's_{k'n'}}} q_{i's_{k'n'}m} * v^{r}\right) * \mu_{i's_{k'n'}j}}{Lp_{i'j}^{\tau}} * \dfrac{\sum_{c\in\Delta} y_{is_{kn}i's_{kn}'c}}{\sum_{d\in\Delta}\phi_{i's_{k'n'}d}} - \sum_{\theta\in T}\sum_{j''\in M^{\theta is_{kn}}}\dfrac{q_{is_{kn}j''} * v^{\theta}}{Lp_{ij}^{\tau}}\right]}$ | $\forall t\in T$<br>$\forall i\in B$<br>$\forall s_{kn}\in S$<br>$\forall j\in M^{tis_{kn}}$ | (a) |
| $(\rho_{DL})_{is_{kn}j} \ge 0$ | $\forall t\in T$<br>$\forall i\in B$<br>$\forall s_{kn}\in S$<br>$\forall j\in M^{tis_{kn}}$ | (b) |
| $\sum_{i\in B}\sum_{s_{kn}\in S}(\rho_{DL})_{is_{kn}j} \ge (\rho_{DL})^{t}$ | $\forall t\in T$<br>$\forall j\in M^{t}$ | (c) |
| $\rho_{is_{kn}j} \le \mu_{is_{kn}j} * H$ | $\forall t\in T$<br>$\forall j\in M^{t}$<br>$\forall i\in B$<br>$s_{kn}\in S$ | (d) |

Constraint (a) is similar to constraint (2.8). The symbol $\varepsilon$ presents a very small number and $\varepsilon_2$ is larger than $\varepsilon_1$. These two artificial constants would be useful solving the Lagrangian Relaxation subproblem.

Constraint (b) ensures the decision variable SIR larger than 0. Constraint (c) ensures the combination of SIR larger than the actual requirement. Constraint (d) ensures the decision variable SIR could only be given a number larger than 0 when the mobile *j* is in the coverage of sector $s_{kn}$ of base station *i*.

The subproblem would be the form below.

min

$$
\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^{5}_{tis_{kn}j}
\left(
\begin{array}{l}
\left\{
\begin{array}{l}
10^{-13.4} * \sum_{f\in\Delta}\phi_{is_{kn}f} * \frac{W}{BN} \\
+(1-\alpha)\left(\sum_{q\in T}\sum_{j'\in M^{tis_{kn}}, j'\neq j}\frac{q_{is_{kn}j'} * v^{q}}{Lp^{\tau}_{ij}}\right) \\
+\sum_{i'\in B}\sum_{s_{k'n'}\in S}\left(\frac{\left(\sum_{r\in T}\sum_{m\in M^{ri's_{k'n'}}} q_{i's_{k'n'}m} * v^{r} * \mu_{i's_{k'n'}j}\right)}{Lp^{\tau}_{i'j}} * \frac{\sum_{c\in\Delta} y_{is_{kn}i's_{kn}'c}}{\sum_{d\in\Delta}\phi_{i's_{k'n'}d}}\right) \\
-\sum_{\theta\in T}\sum_{j''\in M^{\theta is_{kn}}}\frac{q_{is_{kn}j''} * v^{\theta}}{Lp^{\tau}_{ij}}
\end{array}
\right\} \\
-\frac{\frac{q_{is_{kn}j}}{Lp^{\tau}_{ij}} * \frac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{(R_{DL})^{t}(BN)} + \varepsilon_{2}}{\left[(\rho_{DL})_{is_{kn}j} + \varepsilon_{1}\right]}
\end{array}
\right)
$$

$$
+\sum_{t\in T}\sum_{j\in M^{t}} u^{6}_{tj}\left((\rho_{DL})^{t} - \sum_{i\in B}\sum_{s_{kn}\in S}(\rho_{DL})_{is_{kn}j}\right)
$$

$$
+\sum_{t\in T}\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\sum_{j\in M^{is_{kn}j}} u^{7}_{tis_{kn}jk} q_{is_{kn}j}
$$

$$
+\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta} u^{8}_{is_{kn}i's_{k'n'}b}\left(y_{is_{kn}i's_{kn}'b} - \phi_{is_{kn}b}\right)
$$

$$
+\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta} u^{9}_{is_{kn}i's_{k'n'}b}\left(\phi_{is_{kn}b} + \phi_{i's_{kn}'b} - 1 - 2y_{is_{kn}i's_{kn}'b}\right)
$$

$$
-\sum_{t\in T}\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{j\in M^{tis_{kn}}} u^{3}_{tis_{kn}j} * q_{is_{kn}j}
$$

The final result of the rewrite of the subproblem would be just as below.

min

$$\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\left(\begin{array}{l}\sum_{t\in T}\sum_{j\in M^{tis_{kn}}} u^5_{tis_{kn}j}10^{-13.4}*\sum_{f\in\Delta}\phi_{is_{kn}f}*\frac{W}{BN}-\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta}\phi_{is_{kn}b}\left(u^8_{is_{kn}i's_{k'n'}b}-u^9_{is_{kn}i's_{k'n'}b}-u^9_{i's_{k'n'}is_{kn}b}\right)\\ -\sum_{t\in T}\sum_{j\in M^{tis_{kn}}} q_{is_{kn}j}\left(\begin{array}{l}\sum_{q\in T}\sum_{j'\in M^{tis_{kn}}}\left(\alpha u^5_{tis_{kn}j'}\frac{v^q}{Lp^\tau_{ij'}}\right)+(1-\alpha)\frac{v^t}{Lp^\tau_{ij}}\\ +\frac{\frac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{(R_{DL})^t(BN)}u^5_{tis_{kn}j}}{Lp^\tau_{ij}\left[(\rho_{DL})_{is_{kn}j}+\varepsilon_1\right]}-u^7_{tis_{kn}jk}+u^3_{tis_{kn}j}\end{array}\right)\\ +\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta} y_{i's_{k'n'}is_{kn}b}\left(\begin{array}{l}\frac{\sum_{r\in T}\sum_{m\in M^{ris_{kn}}} q_{is_{kn}m}*v^r}{\sum_{d\in\Delta}\phi_{is_{kn}d}}\sum_{t\in T}\sum_{j\in M^{ti's_{k'n'}}}\frac{(\mu_{is_{kn}j})u^5_{ti's_{k'n'}j}}{Lp^\tau_{ij}}\\ +u^8_{i's_{k'n'}is_{kn}b}-2u^9_{i's_{k'n'}is_{kn}b}\end{array}\right)\\ -\sum_{t\in T}\sum_{j\in M^{tis_{kn}}}\frac{\varepsilon_2 u^5_{tis_{kn}j}}{\left[(\rho_{DL})_{is_{kn}j}+\varepsilon_1\right]}-\sum_{t\in T}\sum_{j\in M^t}(\rho_{DL})_{is_{kn}j}u^6_{tj}\end{array}\right)$$

$$-\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta}u^9_{is_{kn}i's_{k'n'}b}+\sum_{t\in T}\sum_{j\in M^t}u^6_{tj}(\rho_{DL})^t$$

It is a subproblem which cannot be easily solved. To solve this subproblem, the decision variable $(\rho_{DL})_{is_{kn}j}$ must be exhaustively searched. Dynamic programming must be used to solve this problem for all interactivity between $(\rho_{DL})_{is_{kn}j}$ and $q_{is_{kn}j}$ could not be separated. Therefore, an algorithm like knapsack must be implemented. We omit the soft handover effect for simplicity.

**Model Modification:**

Though we omit the effects of soft handoff, the computation time is still too slow for solving our subproblems. We have to make a little change to the formula.

The idea is to make a mobile station present multi-mobiles. We need to add a constant to present this modification.

| | |
|---|---|
| *AmU* | The number of user node *j* presents. |

Both uplink and downlink constraints should be modified as follow.

$$uplink:(\rho_{UL})^t \left( \begin{array}{l} P_N + \\ \sum_{o\in T}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{e\in M^{ti's_{k'n'}}} p^o_{i's_{k'n'}} v^o x_{ei's_{k'n'}} * \mu_{is_{kn}e} \frac{Lp^{\tau}_{i'e}}{Lp^{\tau}_{ie}} \\ -\frac{p^t_{is_{kn}}}{AmU} \end{array} \right) \le \frac{p^t_{is_{kn}}}{AmU} \frac{W^u}{(R_{UL})^t}$$

$$downlink:(\rho_{DL})^t \left\{ \begin{array}{l} 10^{-13.4} * \sum_{f\in\Delta} \phi_{is_{kn}f} * \frac{W}{BN} \\ +(1-\alpha)(\sum_{q\in T}\sum_{j'\in M^{qis_{kn}}} \frac{q_{is_{kn}j'} * v^q}{Lp^{\tau}_{ij}} - \frac{q_{is_{kn}j} * v^t}{AmU * Lp^{\tau}_{ij}}) \\ +\sum_{i'\in B}\sum_{s_{k'n'}\in S} \frac{\sum_{r\in T}\sum_{m\in M^{ri's_{k'n'}}} q_{i's_{k'n'}m} * v^r * \mu_{i's_{k'n'}j}}{Lp^{\tau}_{i'j}} * \frac{\sum_{c\in\Delta} y_{is_{kn}i's_{kn}'c}}{\sum_{d\in\Delta}\phi_{i's_{k'n'}d}} \\ -\sum_{\theta\in T}\sum_{j''\in M^{\theta is_{kn}}} \frac{q_{is_{kn}j''} * v^{\theta}}{Lp^{\tau}_{ij}} \end{array} \right\}$$

$$\le \left[ \left( \frac{q_{is_{kn}j}}{AmU * Lp^{\tau}_{ij}} * \frac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{(R_{DL})^t (BN)} \right) + \left(1 - x_{jis_{kn}}\right) * H \right]$$

The subproblem should be modified as well. In this thesis experiment, we let 1 node *j* present 3 users.

## 3.4 Alternative approach to model downlink SIR problem and complexity comparison

There is another way to model the same problem. We make $y_{is_{kn}i's_{k'n'}b} = \phi_{is_{kn}b} * \phi_{i's_{k'n'}b}$ in the thesis and the subproblem2 is not an easy problem to solve. However, we could make $y_{is_{kn}i's_{k'n'}by} = \phi_{is_{kn}b} * \phi_{i's_{k'n'}b} * q_{is_{kn}j}$ to make the problem easier to solve. Adding the constraints below and we could make $y_{is_{kn}i's_{k'n'}by} = \phi_{is_{kn}b} * \phi_{i's_{k'n'}b} * q_{is_{kn}j}$ .

$$q_{is_{kn}j} \le Q_{\max}$$

| |
|---|
| $y_{is_{kn}i's_{k'n'}bj} \le \phi_{is_{kn}b} * Q_{\max}$ |
| $y_{is_{kn}i's_{k'n'}bj} \le \phi_{i's_{k'n'}b} * Q_{\max}$ |
| $y_{is_{kn}i's_{k'n'}bj} \le q_{is_{kn}j}$ |
| $y_{is_{kn}i's_{k'n'}bj} \ge \left(\phi_{is_{kn}b} + \phi_{i's_{k'n'}b} - 2\right) * Q_{\max} + q_{is_{kn}j}$ |
| $y_{is_{kn}i's_{k'n'}bj} \ge 0$ |

The downlink SIR constraint would be modified below.

$$(\rho_{DL})^t \le \frac{\frac{q^{t}_{is_{kn}}}{Lp^{\tau}_{ij}} * \frac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{(R_{DL})^t\,(BN)} + \left(1 - x_{jis_{kn}}\right) * epsilon}{\left[\begin{array}{l} 10^{-13.4} * \sum_{f\in\Delta}\phi_{is_{kn}f} * \frac{W}{BN} \\ + (1-\alpha)\left(\sum_{q\in T}\sum_{j'\in M^{qis_{kn}},\, j'\neq j}\frac{q^{q}_{is_{kn}} * v^{q}}{Lp^{\tau}_{ij}}\right) \\ + \sum_{i'\in B}\sum_{s_{k'n'}\in S}\left(\frac{\sum_{r\in T}\sum_{m\in M^{ri's_{k'n'}}}\sum_{c\in\Delta} y_{i's_{k'n'}is_{kn}cm} * v^{r}}{Lp^{\tau}_{i'j}} * \frac{\mu_{i's_{k'n'}j}}{\sum_{d\in\Delta}\phi_{i's_{k'n'}d}}\right) \\ - \sum_{\theta\in T}\sum_{j''\in M^{\theta is_{kn}}}\frac{q^{\theta}_{is_{kn}} * v^{\theta}}{Lp^{\tau}_{ij}} \end{array}\right]}$$

Replacing $y_{is_{kn}i's_{kn}'b} \ge \frac{\phi_{is_{kn}b} + \phi_{i's_{k'n'}b} - 1}{2}$ by $y_{is_{kn}i's_{k'n'}bj} \ge \left(\phi_{is_{kn}b} + \phi_{i's_{k'n'}b} - 2\right) * Q_{\max} + q_{is_{kn}j}$ ,

we could let new LR subproblem2 be modeled below.

min

$$
\sum_{i\in B}\sum_{k\in K}\sum_{s_{kn}\in S}\left(
\begin{array}{l}
\sum_{t\in T}\sum_{j\in M^{tis_{kn}}} u^{5}_{tis_{kn}j} * \left(\rho_{DL}\right)^{t} * 10^{-13.4} * \sum_{f\in\Delta}\phi_{is_{kn}f} * \frac{W}{BN} \\
-\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta}\phi_{is_{kn}b}\left(\sum_{t\in T}\sum_{j\in M^{ti's_{k'n'}}} u^{8}_{i's_{k'n'}is_{kn}bj} - \sum_{t'\in T}\sum_{j\in M^{t'is_{kn}}} u^{9}_{is_{kn}i's_{k'n'}bj}Q_{\max} - \sum_{t''\in T}\sum_{j\in M^{t''i's_{k'n'}}} u^{9}_{i's_{k'n'}is_{kn}bj}Q_{\max}\right) \\
-\sum_{t\in T}\sum_{j\in M^{tis_{kn}}} q_{is_{kn}j}\left(
\begin{array}{l}
\left[\begin{array}{l}
\sum_{q\in T}\sum_{j'\in M^{qis_{kn}}}\left(\rho_{DL}\right)^{q}\left(\alpha u^{5}_{qis_{kn}j'}\frac{v^{t}}{Lp^{\tau}_{ij'}}\right) \\
+u^{5}_{tis_{kn}j} * \left(\rho_{DL}\right)^{t}\left(1-\alpha\right)\frac{v^{t}}{Lp^{\tau}_{ij}} \\
+\frac{W\left(\sum_{b\in\Delta}\phi_{is_{kn}b}\right)}{Lp^{\tau}_{ij}\left(R_{DL}\right)^{t}\left(BN\right)}u^{5}_{tis_{kn}j}
\end{array}\right] \\
-u^{6}_{tis_{kn}j} - u^{7}_{tis_{kn}jk} + u^{3}_{tis_{kn}j} - \sum_{i'\in B}\sum_{S_{k'n'}\in S}\sum_{b\in\Delta}u^{9}_{is_{kn}i's_{k'n'}bj}
\end{array}\right) \\
+\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta}\sum_{r\in T}\sum_{m\in M^{ris_{kn}}} y_{is_{kn}i's_{k'n'}bm}\left(
\begin{array}{l}
\frac{v^{r}}{\sum_{d\in\Delta}\phi_{is_{kn}d}} * \sum_{t\in T}\sum_{j\in M^{ti's_{k'n'}}}\frac{\left(\rho_{DL}\right)^{t}\left(\mu_{is_{kn}j}\right)u^{5}_{ti's_{k'n'}j}}{Lp^{\tau}_{ij}} \\
+u^{8}_{is_{kn}i's_{k'n'}bm} - u^{9}_{is_{kn}i's_{k'n'}bm}
\end{array}\right)
\end{array}\right)
$$

$$
-\sum_{i\in B}\sum_{s_{kn}\in S}\sum_{i'\in B}\sum_{s_{k'n'}\in S}\sum_{b\in\Delta}\sum_{t\in T}\sum_{j\in M^{tis_{kn}}} u^{9}_{is_{kn}i's_{k'n'}bj}\,2Q_{\max}
$$

subject to:

| | |
|---|---|
| $q_{is_{kn}j} \le \mu_{is_{kn}j} * H$ | $\forall t\in T,\ \forall j\in M^{t}$ <br> $\forall i\in B,\ s_{kn}\in S$ |
| $\sum_{t\in T}\sum_{j\in M^{tis_{kn}}} q_{is_{kn}j} \le P_{BS}$ | $\forall i\in B,\ \forall s_{kn}\in S$ |
| $\phi_{is_{kn}b} = 0$ or $1$ | $\forall i\in B$ <br> $\forall s_{kn}\in S$ <br> $\forall b\in\Delta$ |
| $\sum_{b=1}^{BN+1}\left(\phi_{is_{kn}b} - \phi_{is_{kn}b-1}\right)^{2} = 2$ | $\forall i\in B$ <br> $\forall s_{kn}\in S$ |
| $y_{is_{kn}i's_{k'n'}bj} \le \phi_{is_{kn}b} * Q_{\max}$ | $\forall i'\in B,\ \forall s_{k'n'}\in S$ <br> $\forall i\in B,\ \forall s_{kn}\in S,\ \forall b\in\Delta$ <br> $\forall j\in M^{tis_{kn}}$ |
| $y_{is_{kn}i's_{k'n'}bj} \le q_{is_{kn}j}$ | $\forall i'\in B,\ \forall s_{k'n'}\in S$ <br> $\forall i\in B,\ \forall s_{kn}\in S,\ \forall b\in\Delta$ <br> $\forall j\in M^{tis_{kn}}$ |

| | |
|---|---|
| $y_{is_{kn}i's_{k'n'}bj} \ge 0$ | $\forall i \in B,\ \forall s_{kn} \in S$ <br> $\forall i' \in B,\ \forall s_{k'n'} \in S,\ \forall b \in \Delta$ <br> $\forall j \in M^{tis_{kn}}$ |
| $q_{is_{kn}j} \le Q_{\max}$ | $\forall t \in T$ <br> $\forall j \in M^t$ <br> $\forall i \in B$ <br> $s_{kn} \in S$ |

The constraint $y_{is_{kn}i's_{k'n'}bj} \le q_{is_{kn}j}$ is not relaxed and there is a simple algorithm to solve the problem.

By calculating the indicator value

$$\left( \left[ \begin{array}{l} \sum_{q \in T} \sum_{j' \in M^{qis_{kn}}} (\rho_{DL})^q \left( \alpha u^5_{qis_{kn}j'} \frac{v^t}{Lp^\tau_{ij'}} \right) \\ +u^5_{tis_{kn}j} * (\rho_{DL})^t (1-\alpha) \frac{v^t}{Lp^\tau_{ij}} \\ + \frac{W\left( \sum_{b \in \Delta} \phi_{is_{kn}b} \right)}{Lp^\tau_{ij} (R_{DL})^t (BN)} u^5_{tis_{kn}j} \end{array} \right] \\ -u^6_{tis_{kn}j} - u^7_{tis_{kn}jk} + u^3_{tis_{kn}j} - \sum_{i' \in B} \sum_{S_{k'n'} \in S} \sum_{b \in \Delta} u^9_{is_{kn}i's_{k'n'}bj} \right)$$

of $q_{is_{kn}j}$, we could subtract indicator value

$$\left( \begin{array}{l} \frac{v^r}{\sum_{d \in \Delta} \phi_{is_{kn}d}} * \sum_{t \in T} \sum_{j \in M^{ti's_{k'n'}}} \frac{(\rho_{DL})^t (\mu_{is_{kn}j}) u^5_{ti's_{k'n'}j}}{Lp^\tau_{ij}} \\ +u^8_{is_{kn}i's_{k'n'}bm} - u^9_{is_{kn}i's_{k'n'}bm} \end{array} \right)$$

of decision variables $y_{i's_{k'n'}is_{kn}bm}$ for all $i', s_{k'n'}$ and $b$ if the value <0 from this value and we get the full information of the $q_{is_{kn}j}$ indicator value. Let the full information be $im_{is_{kn}j}$, and we could arranging all $im_{is_{kn}j}$ until the value <0. Assign the power one by one from large to small; we could solve the subproblem easily.

**Complexity Comparison**

The complexity of the original model is

$I*S*\frac{F}{2}\left(J+I*S*F*F+J^2+J^2+I*S*F*\frac{T^2}{2}(J)\right)$ and the complexity of the new model is $I*S*\frac{F}{2}\left(J+I*S*F*F*J+J\left(J+I*S*F+I*S*F(J)\right)+J^2\right)$.

Table 3-1 Complexity symbol definition

| | |
|---|---|
| I | Base Station number. |
| S | Total probability of the cells deployment<br>When K=5, S=10. |
| F | Frequency number. |
| J | Mobile number covered by each cell. |
| T | Exhaustive search the total downlink power probability. In this thesis, we divide the total downlink power in 80 parts equally. |

On the surface, the complexity of the original model is higher than the new one. However, the experiment result is not so simple. During the iterations of solving the subproblem, the deployment trend would be more and more apparently and there would be some cells not chosen for transmitting power. The complexity of the original model would be $I*S*\frac{F}{2}\left(J+I*S*F*F+J^2+J^2+I*S*F*\frac{T^2}{2}(J)\right)$ in calculating some cells for the calculation could be left out. However, the new model complexity is not so lucky. For all cells, the indicator value should be calculated completely and therefore the omission is much less than the original model. The complexity is $I*S*\frac{F}{2}\left(J+I*S*F*F*J+J\left(J+I*S*F+I*S*F(J)\right)+J^2\right)$ larger than the original model.

The required memory of the new model is much larger than the original too. The results of the new model experiment are not good as the original model, and therefore we forsake the way to model the problem even the subproblem could be solved easier.

# Chapter 4 Getting Primal Feasible Solutions

To deal with our problem, we choose Lagrangian relaxation and subgradient method as our tools. Thus, we can get not only a theoretical lower bound of primal feasible solution, but also get some hints from solutions to the Lagrangian relaxation problem (LR) and Lagrangian multipliers resulted from iterations to help us to get our primal feasible solution under each solving dual problem iteration.

After an iteration solving dual problem, we will get a set of decision variable. If the calculated decision variables happen to satisfy all constraints in the primal problem, a primal feasible solution is found. However, it may not be feasible in dealing with our problems; for example, it may violate the constraints that we relaxed before. In addition to being a bounding procedure of large scale optimization problems, the solution procedure of Lagrangian dual problems usually provides important implications and nice starting points, which sheds light on the searching of good primal solutions. In order to ensure the decision variables are feasible, check or modification is needed, such as drop-and-add heuristics.

Here we propose a heuristic for getting primal feasible solution of this problem. It includes deployment and sectorization configuration selection, downlink power adjustment and uplink power adjustment.

## 4.1 Heuristic for deployment selection

Throughout the model, we know the decision variable $x_{jis_{kn}}$ is very important. By solving SUB 3.3, we determined where to deployment the base station and the sector configuration. However, we may select none of the candidate base stations as well. To get the feasible sets of solutions, we must build suitable base stations and sector configurations first. Here we propose a heuristic based on $x_{jis_{kn}}$ to get a feasible solution of this problem, it described in the following Algorithm 4.1.

Table 4-1 Algorithm 4.1: Heuristic for deployment selection

| |
|---|
| **Algorithm 4.1** |
| **Step 1.** For each mobile station *j*, there should be at least one base station handle it. For each base station not deployed, there would be a record shows the importance. The importance is calculated by multiplier $u^4_{tis_{kn}jk} * x_{jis_{kn}}$ for $x_{jis_{kn}}$ is the most important decision variable and $u^4_{tis_{kn}jk}$ means the weight of the constraint. If $u^4_{tis_{kn}jk}$ is large and $x_{jis_{kn}}$ is 1 means the trend tend to set $a_{ik}$ =1. If $u^4_{tis_{kn}jk}$ is very small, it means the constraint could be omitted and whether $x_{jis_{kn}}$ or $a_{ik}$ is 1 or 0 is not important. |
| **Step 2.** For each mobile station *j*, if there is no base station set up for it. The most important base station in the coverage of *j* calculated at Step 1 would be deployed. |
| **Step 3.** Just like step 2, the sector configuration would be selected. The importance of each sector is calculated as step 1. |
| **Step 4.** For each cell of each base station, ensure all connections |

| | |
|---|---|
| | disconnected if the base station or the sector is not chose and ensure each mobile connect to the nearest base station if $x_{jis_{kn}}$ determined in subproblem1 is 1. If there is a connection, there should be a power transmitted. If there is no connection, there should not be any power transmitted. The relationship of $x_{jis_{kn}}$ and $q_{is_{kn}j}$ should be maintained. |
| **Step 5.** | For each mobile station, there should be exactly only one connection to the base stations. |
| **Step 6.** | For each base station deployed, calculate the revenue which is the building cost subtracting from the total users profits. If the revenue<0, the base station should not be built and all connections should be break and all power transmitted should be 0. |

## 4.2 Heuristic for Uplink Power Adjustment

For each cell deployed, the received power should be larger than the interference.

If the received power is less than the interference, the received power is increased if the adjusted power is less than the maximum power it could received. If there is any mobile station fail to increase its power for the mobile station power limitation, the connection between mobile and base station would be broke and so does the transmitted power from the base station to the mobile station.

If the received power is larger than the interference, we considered to decrease the received power for random.

Check the revenue for each base station again. Cancel the deployment of any base station not profitable.

## 4.3 Heuristic for Downlink Power Adjustment

The same as uplink, for each connected mobile station, the received power at mobile station should be larger than the received interference.

If the SIR could not be satisfied, try to increase the power under the total power limitation or break the connection if there is no surplus power to provide it.

Check the revenue for each base station again. Cancel the deployment of any base station not profitable.

# Chapter 5 Computational Experiments

## 5.1 Lagrangian Relaxation Base Algorithm (LR)

This algorithm is based on the mathematical formulation described in Chapter 2. The relaxed problem is then optimally solved as described in Chapter 3 to get a lower bound to the primal problem. We adopt a heuristic algorithm to readjust downlink and uplink power arrangement and solve the deployment problem in Chapter 4. And we use a subgradient method to update the Lagrangian multipliers. To sum up, the Lagrangian relaxation based algorithm (LR) is used iteration by iteration as follow.

Table 5-1 The full process of the Lagrangian relaxation based algorithm.

**Algorithm 5-1**

**Step 1.** Set configuration for the construct distribution of base stations and information of every traffic type, and generate mobile users.

**Step 2.** Calculate constant parameters, such as thermal noise, path loss or other constants and assign Lagrangian relaxation improve counter to 25.

**Step 3.** Initialize multipliers.

**Step 4.** According to given multipliers, optimally solve these problems of

SUB 3.1, SUB 3.2, SUB 3.3 to get the value of $Z_{dual}$

**Step 5.** According to heuristics of Chapter 4, we get the total revenue, the value of $Z_{IP}$

**Step 6.** If $Z_{IP}$ is small than $Z^*_{IP}$, we assign $Z^*_{IP}$ to equal $Z_{IP}$. Otherwise, we minus 1 from improve counter.

**Step 7.** Calculate step size and adjust Lagrangian relaxation multipliers by using the subgradient method as described in section 3.2.

**Step 8.** Iteration counter increases by 1. If iteration counter is over the threshold of the system, stop the program. And, ZIP* is our best solution. Otherwise, repeat Step 4.

## 5.2 Parameters and Cases of the Experiment

The parameters used for all cases are listed in Table 5-1. The SIR requirement, revenue and cost of every traffic type are listed in Table 5-2 and Table 5-3.

Table 5-2 Parameters of the System

| | |
|---|---|
| Voice activity factor | 0.6 |
| Data activity factor | 1.0 |
| Maximum power of base station | 24W |
| Maximum power of a base station to a mobile station | 0.8W |
| Maximum power of mobile station | 0.2W |
| Background noise power | -164.0+10*log10(W(kHz)) (in dB) |
| Orthogonality factor | 0.5 |
| Attenuation factor | 3 |
| Distance for calculate the path loss in attenuation factor2 | 1km |

| | |
|---|---|
| Uplink frequency band | 10MHz |
| Downlink frequency band | 10MHz |
| Downlink frequency number | 3 |

Table 5-3 $E_b/N_0$ and SIR Requirement for Every Traffic Type

| Traffic Type | Uplink | | Downlink | |
|---|---|---|---|---|
| | $E_b/N_0$ (db) | SIR requirement | $E_b/N_0$ (db) | SIR requirement |
| Voice 12.2 kbps | 2.9 | 0.0062 | 4.4 | 0.0088 |
| Data 144 kbps | 0.4 | 0.0411 | 2.3 | 0.0637 |

Table 5-4 Revenue of Every Traffic Type

| | Revenue |
|---|---|
| Voice 12.2 kbps / 12.2 kbps | 30(3 Mobile stations) |
| Data 144 kbps / 144 kbps | 108(3 Mobile stations) |

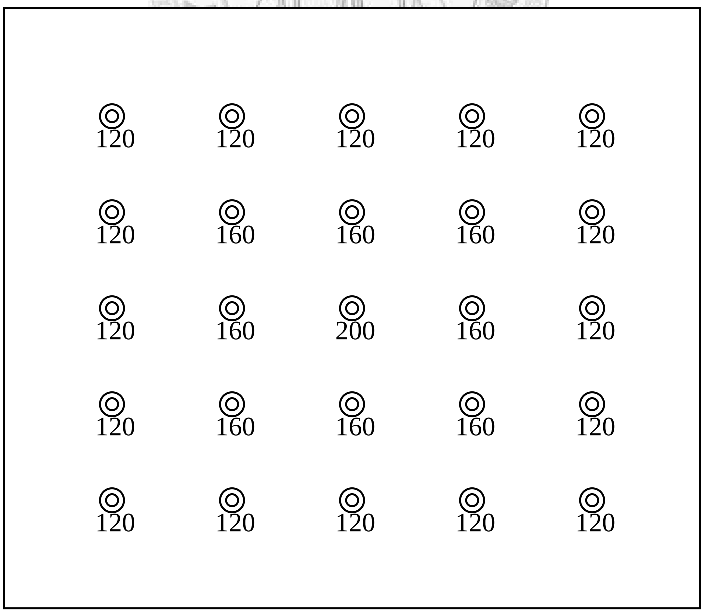



Figure 5-1 Candidate base stations and the cost of deployment – 25BS

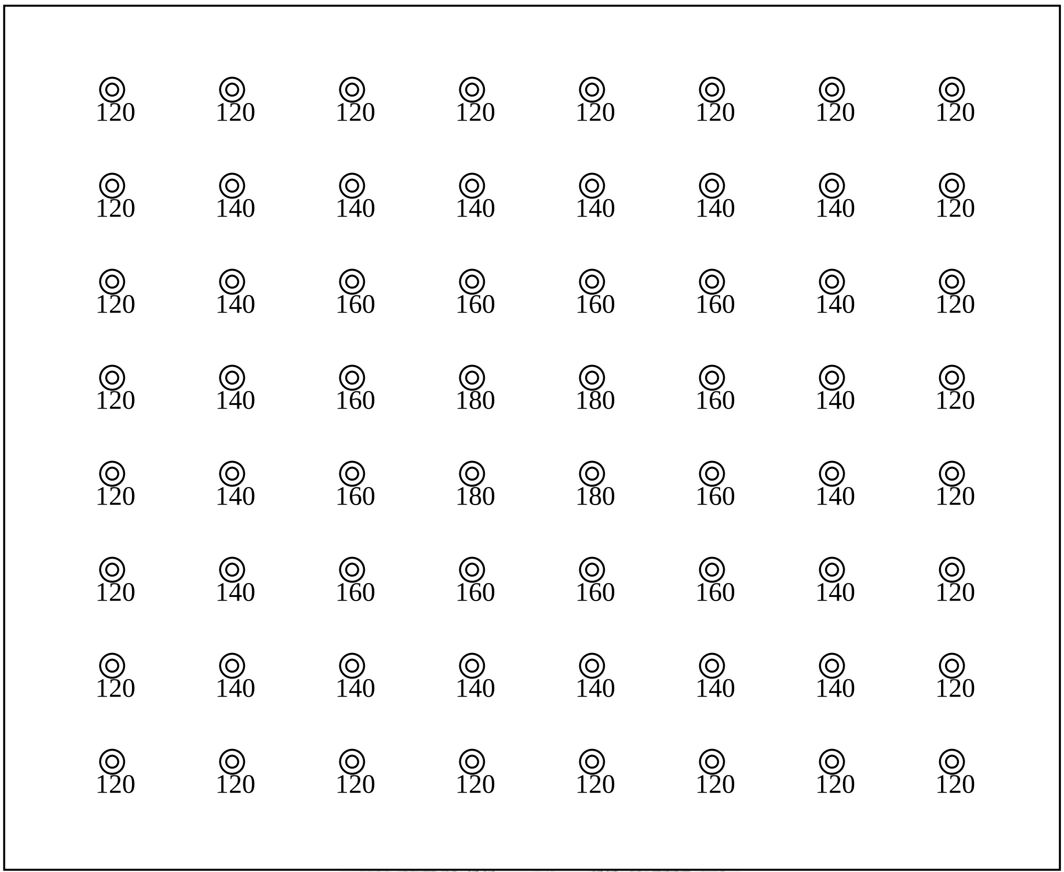
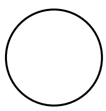
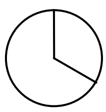
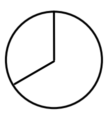
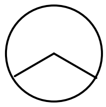
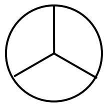



Figure 5-2 Candidate base stations and the cost of deployment – 64BS

Table 5-5 Cost of each type of sector configurations

| | Configuration | Cost |
|---|---|---|
| Configuration 1 | Omni directional  | 300 |
| Configuration 2 |  | 600 |
| Configuration 3 |  | 600 |

| | | |
|---|---|---|
| Configuration 4 |  | 600 |
| Configuration 5 |  | 900 |

In Case1~6 , the number of candidate base station ($|B|$) are given to 25, and their distribution in Figure 5-2 in 4.8 km * 4.8 km environment. In Case 7~9, the number of candidate base station ($|B|$) are given to 64, and their distribution in Figure 5-3 in 7.2 km * 7.2 km environment. The number of traffic type is 2. The experiment cases list in Table 5-5. Each case from 1~6 perform 6 rounds and each round runs 500 iterations and each case from 7~9 perform 6 rounds and each round runs 600 iterations.

Table 5-6 Experiment Cases

| | Number of nodes | Ratio of Voice Users | Ratio of Data Users |
|---|---|---|---|
| Case 1 | 250(750MS) | 75% | 25% |
| Case 2 | 250(750MS) | 67% | 33% |
| Case 3 | 250(750MS) | 50% | 50% |
| Case 4 | 300(900MS) | 75% | 25% |
| Case 5 | 300(900MS) | 67% | 33% |
| Case 6 | 300(900MS) | 50% | 50% |
| Case 7 | 750(2250MS) | 75% | 25% |
| Case 8 | 750(2250MS) | 67% | 33% |
| Case 9 | 750(2250MS) | 50% | 50% |

## 5.3 Experiment result

The Lagrangian-based heuristic and the primal one are named “LR” and “SA”, respectively. We denote our dual solution as "$Z_{dual}$". "Gap" is calculated to evaluate our Lagrangian-based heuristic. Gap = $\frac{LR - Z_{dual}}{LR}$ * 100%. "Improvement" is our Lagrangian-based heuristic improvement on the simpler one — SA. Improvement = $\frac{SA - LR}{SA}$ * 100% and the Average Time means required time for 500 iterations.

SA is designed based on the "Getting Primal Feasible Solution", each mobile station is greedily chosen to the nearby base station and the decision variables *x* to each sector type are randomly chosen. Ignore the FDMA effect, SA chooses all 10MHz in both uplink and downlink. We select the maximum number of mobiles' choice to decide the sector type. Each SA value from Case1~6 tests 5000 iterations and each SA value from case7~9 tests 4000 iterations and all of them select the best result.

Table 5-7 Case 1~6 Experiment result (Best: Choose the best LR result)

| | LR | $Z_{dual}$ | SA | Gap | Improvement | Time(seconds) |
|---|---|---|---|---|---|---|
| Case 1 | -7668 | -10911.4973 | -4376 | 42.30% | 75.23% | 2819 |
| Case 2 | -8780 | -13746.2521 | -6410 | 56.56% | 36.97% | 2907 |
| Case 3 | -9678 | -15146.4197 | -7118 | 56.50% | 35.97% | 2620 |
| Case 4 | -9134 | -13177.2044 | -6044 | 44.27% | 51.13% | 3798 |
| Case 5 | -11090 | -15541.7494 | -8356 | 40.14% | 32.71% | 3916 |
| Case 6 | -12054 | -18277.4089 | -9808 | 51.63% | 22.90% | 3692 |

Table 5-8 Case 1~6 Experiment result (Average)

| | LR | $Z_{dual}$ | SA | Gap | Improvement | Time(seconds) |
|---|---|---|---|---|---|---|
| Case 1 | -7452 | -10544.3237 | -4376 | 41.50% | 70.29% | 2819 |
| Case 2 | -8138 | -12800.0289 | -6410 | 57.29% | 26.96% | 2907 |
| Case 3 | -9657 | -16526.5720 | -7118 | 71.12% | 35.67% | 2620 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Case 4 | -8706 | -13325.3672 | -6044 | 53.06% | 44.04% | 3798 |
| Case 5 | -10428 | -15764.0478 | -8356 | 51.17% | 24.79% | 3916 |
| Case 6 | -11556 | -19245.6750 | -9808 | 66.54% | 17.83% | 3692 |

Table 5-9 Case 7~9 Experiment result (Best: Choose the best LR result)

| | LR | $Z_{dual}$ | SA | Gap | Improvement | Time(seconds) |
|---|---|---|---|---|---|---|
| Case 7 | -22100 | -33552.7561 | -15796 | 51.82% | 39.91% | 54123 |
| Case 8 | -24882 | -40300.6228 | -18002 | 61.97% | 38.22% | 50037 |
| Case 9 | -29142 | -49212.5867 | -23452 | 68.87% | 38.60% | 47942 |

Table 5-10 Case 7~9 Experiment result (Average)

| | LR | $Z_{dual}$ | SA | Gap | Improvement | Time(seconds) |
|---|---|---|---|---|---|---|
| Case 7 | -20862 | -33360.1703 | -15796 | 58.423% | 32.07% | 54123 |
| Case 8 | -23046 | -40758.8171 | -18002 | 76.86% | 28.01% | 50037 |
| Case 9 | -28752 | -49227.7215 | -23452 | 71.21% | 22.60% | 47942 |

## 5.4 Result Discussion

In our computational results, the proposed Lagrangian relaxation base algorithm in most cases can get remarkable solution quality. Although the gap in Case 7, 8 and 9 is larger than other cases, the proposed Lagrangian relaxation algorithm still has obvious improvements compared to the simple primal heuristic. Time consumption is another good issue. From case 7 to 9, SA needs more than 4 hours to complete the calculation and could not give any optimization proof. LR based algorithm would be more powerful when the environment is larger.

# Chapter 6 Conclusion

## 6.1 Summary

As WCDMA system have emerged as a promising candidate of $3^{rd}$ generation wireless telecommunication system. An effective deployment algorithm which chooses good base station locations not only lower down the cost of deployment but provides service to more users and gets more revenue. It would provide much benefit to system operators. WCDMA system has many particular techniques and to the best of our knowledge, there are no mathematical formulation have proposed and solved both considering these issues.

To solve this problem, we propose an approach to WCDMA base station deployment problem to maximize the system operator’s revenue while take QoS constraint, capacity constraint, sector configuration, FDMA and voice/data rate service issues into account. The outcome of this thesis will be helpful for system subscribers to make integrated decision.

We can express our achievements in terms of formulation and performance. In terms of formulation, we model a mathematical expression to describe the deployment problem in voice/data integrated WCDMA wireless communication networks. We not only formulated the FDMA constraint which force the frequency continuity but formulated the way FDMA interact with transmission power. The generic model would be a contribution for WCDMA design with

FDMA issue. In terms of performance, our Lagrangian relaxation based solution has more significant improvement than other intentional algorithm.

## 6.2 Future Work

There are four points could be discussed further.

First, the FDMA in uplink could be modeled as well. However, the way to model uplink SIR requirement might have to be changed. As the way we modeled downlink SIR requirement, the decision variables should be set to MS transmission power but BS received power.

Second, there might be a brighter way to model the soft handover issue to improve the performance.

Third, more variable data rates could be considered as well. There might be a trend in base station deployment issue considering different user allocation. It would be a great contribution if the trend be discovered.

Last, the growth of users could be an interesting problem. How to consider the growth of users and lower down the total deployment cost to get the maximum revenue would be a meaningful problem to investigate.

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出 生 地：台灣省台中縣

出 生 日：中華民國六十八年十二月十三日

學　　歷：八十七年九月至九十一年六月

國立台灣大學資訊管理學系

九十一年九月至九十三年十月

國立台灣大學資訊管理學研究所