

**QoS–Constrained Information Theoretic Capacity  
Maximization in CDMA Systems**

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Candidacy Report

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# Abstract

Code Division Multiple Access (CDMA) has proved to be an efficient and stable means of communication between a group of users which share the same physical medium. Therefore, with the rising demand for high-bandwidth multimedia services on mobile stations, it has become necessary to devise methods for more rigorous management of capacity in these systems. While one of the substantial techniques for regulating capacity in CDMA systems is through power control, the mathematical complexity of the regarding model inhibits useful generalizations and extensions.

In this research, the classical problem of capacity optimization in the reverse link is analyzed. It is shown that the classical formulation is solvable through examination of a finite set of transmission powers, for which closed forms are given. Although, this method leads to a more accurate and faster solution to the classical problem, it is noted that the classical problem is very prone to yielding partial solutions in which the calculated system capacity is not realizable in a practical setting. The developed mathematical model, however, is shown to be applicable to more general definitions of the problem.

The bulk of this research is the analysis of the capacity optimization problem equipped with increasing sets of constraints and utility functions, incorporated into

the problem in order to produce solutions deployable in practical systems. Cases of multiple-class systems are also analyzed and directions for future work on multiple-cell systems are given.

The material presented in this research has been previously published in different forms, as listed in Chapter 4. Mathematical details of the developed methods as well as detailed analysis of the collected experimental results are contained in an appendix available on the author's webpage<sup>1</sup>.

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<sup>1</sup>[http://abadpour.com/?page\\_id=19](http://abadpour.com/?page_id=19)

# Chapter 1

## Introduction

An essential means of regulating the capacity in CDMA systems is through effective transmission power assignment [1]. The necessity of this issue arises from the fact that, for example, in DS/CDMA systems there is universal frequency reuse, meaning that the same carrier frequency and spectral band are shared by all the cells [2]. Hence, it is important to devise a method which is capable of designating optimal transmission powers to the stations, given practical constraints as well as a properly-devised goal function (see a survey in [3]).

The basic approach to the capacity-maximization problem is to define a set of constraints and then to find the solution which satisfies all of them at equality. A simple example of this approach is to find the set of transmission powers which provide a given (often identical) signal to noise ratio (SNR) for all the stations in a cell [4]. For example, in [5], the researchers work on capacity design and analysis of the call admission control using a fixed-SNR approach (also see [6, 7]). A comprehensive and generalized treatment of this topic can be found in [8]. The fixed SNR-approach is

carried out through open-loop power control by single stations using power messages transmitted by the base station in order to instruct each station to either power up or power down [9].

With the introduction of multimedia services to wireless CDMA communications, the goal is no more to provide fixed capacity to all the stations [10], but to maximize the aggregate capacity given a set of constraints [1]. In fact, the addition of other types of services to the conventional voice-only communication channels has urged the need for more control over the rates at which different stations transmit [11]. This is necessary in order to maximize system performance measures including the aggregate capacity [12]. This situation is different from voice-only systems [13] in which the purpose of the power control mechanism was to eliminate the near-far effect through equalizing the SNR of each station [12]. For an early coverage of achieving multiple-rate systems [14] through maintaining fixed chip-rate and different transmission powers refer to [15, 16].

The maximization of the capacity, in this research, is attempted at the reverse link (uplink), because this link is often the limiting link in CDMA communication systems [17, 18]. For an early coverage of the capacity of the reverse link, accompanied by results gathered from field tests, refer to [19] (also see [20]).

Among different channels on the reverse link, this research concentrates on the traffic channels, due to the more demanding conditions they need to satisfy in order to establish stable communications [21]. The work presented in this research is different from power control strategies used in the forward link [22], mainly due to the stringent requirements of the reverse link [23]. It is worth to mention that this work primarily focuses on the system at chip-level, as opposed to some others which also include the different transmission rates of the individual stations [24].

In this chapter, first, the literature of capacity analysis at the reverse link in single-cell systems is analyzed, in Section 1.1. Then, in Section 1.2, multiple-cell systems are briefly reviewed.

## 1.1 Single-Cell Systems

### 1.1.1 Literature Review

Maximizing the capacity of the reverse link in this research is achieved through controlling the transmission powers of the individual stations. Here, the analysis is first carried out in a single-cell system, by assuming that either there is only one cell in the system or that the activity in other cells can be modeled as fixed interference to the current cell [25]. In this research, the term capacity is defined as the rate of transmission of each station. Here, to relate transmission power to rate, Shannon's theorem is used [1, 26]. The adoption of the maximum bound given by Shannon's theorem is based on previously-developed models (see [27] for example).

The system-wide information theoretic capacity of CDMA systems was first analyzed in [25] and then developed further for multi-user networks in [1, 28]. While these works focus on the set of all capacities, more recent research has benefited from the advances in matched filters [1] and the aggregate capacity has been analyzed [27, 29, 30]. In these works, assuming a sub-optimal coding scheme, the mapping between signal to interference ratio (SIR) and throughput is determined by the coding strategy. Subsequently, research in the field has been followed by capitalizing on the assumption of Shannon's capacity. Although, Shannon's theorem gives the maximum bound for the capacity, the existence of coding strategies such as Turbo Coding makes Shannon's

bound practically achievable [1]. It should be emphasized that, here, the assumption of additive white Gaussian noise (AWGN) [31] is necessary for the adoption of the maximum bound on system capacity as given by Shannon's theorem [32].

Analysis of the capacity-maximization problem for a particular group of stations is analyzed in some works. Many of these methods do not have a natural generalization when different groups of customers are incorporated into the problem [24]. For example, in [33] the authors work on a two-class system in which voice users are guaranteed a minimum quality and data users are provided with the highest possible system capacity.

A general category of the research done on optimizing the transmission powers of the reverse link is based on maximizing capacity-oriented, often similarly-defined, objective functions, subject to different sets of constraints (also see [34]). For example, in [8, 35, 36, 37], the authors work on minimizing the transmitted power subject to a minimum SIR requirement, an approach suitable for fixed-SIR voice-only communications. In [38], the authors work on a similar problem with the difference that they formulate the objective function as representing the throughput for delay-tolerant users. In fact, the major difference between these works is the constraints they use and subsequently how much realistic their solution becomes, as a result of the utilized constraints. For example, in [39], the only constraints are a minimum guaranteed SNR and bounds on individual transmission powers. There, first, the problem is constituted as minimizing the aggregate received power. Then, it is reformulated as maximizing the aggregate capacity. A similar problem is looked at in [40], where the authors minimize the aggregate received power in a multiple-cell system subject to power and SNR constraints, where the assignment of the stations to the

cells is to be decided as well. A similar problem is treated in [41, 42] in a stochastic framework.

In a recent paper, *Oh* and *Soong* [43] developed a method for optimizing the aggregate reverse link capacity of a CDMA system given a set of constraints. In that work, the study is carried out in a single cell for aggregate system capacity maximization. The constraints of that problem include minimum signal to noise ratio, maximum and minimum bounds for transmission powers, and maximum bound on the aggregate received power. One of the main contributions of [43] is the inclusion of minimum signal to noise constraint which is devised in order to resolve the issue of impractical solutions produced earlier, as reported in [29, 30]. For simplicity of reference, throughout this research, the problem analyzed in [43] will be addressed as the Classical Single Cell Problem (CSC).

In a cell which contains  $M$  stations, the search space for the CSC is essentially  $M$ -dimensional. However, *Oh* and *Soong* showed that the search can be limited to a multiply of  $M$  number of one-dimensional intervals. For that, they utilized a numerical optimization method [43].

It is worth to mention that while the approach taken in [43] considers the identity function as the utility identifier, there are sound arguments for the appropriateness of concave utility functions for data communication [44]. For instance, it is suggested that the application of concave utility functions in the aggregate-capacity maximization problem leads to intrinsically more fair capacity distributions [45] (Also see [46]).

### 1.1.2 System Model

Capacity of a single point-to-point communication link is well approximated by the Shannon theorem as [1] (also, see [27]),

$$C = B \log_2 \left( 1 + \frac{S}{N} \right). \quad (1.1)$$

Here,  $B$  is the bandwidth and  $\frac{S}{N}$  is the signal to noise ratio of the communication link. In the rest of this report we omit  $B$  knowing that it is a constant multiplier. Hence, here, relative capacities are analyzed. For convenience, the term “relative” will be omitted as well.

Assume that there are  $M$  mobile stations with reverse link gains of  $g_1, \dots, g_M$ , all located in the same cell and communicating with the same base station. The assumption of fixed  $g_i$ s which only consider the path-loss, is based on the assumption that the system is analyzed in time slots of  $T_s$ , where  $T_s \gg \frac{1}{W}$  ( $W$  is the bandwidth), and that the coherence time of the most rapidly varying channel is greater than  $T_s$ . Therefore, in each time slot,  $g_i$ s can be assumed to be constant [29]. It is also worth to mention that the typical time interval during which the shadowing factor is nearly constant for a mobile station is a second or more [2]. Therefore, the assumption of fixed  $g_i$ s is in fact valid for algorithms with run-times significantly less than a second.

Here, we assume that the stations are ordered in the way that,

$$g_1 > \dots > g_M, \quad (1.2)$$

and define power at which the  $i$ -th mobile station is transmitting as  $p_i$ , for which we

have,

$$0 \leq p_i \leq p_{max}. \quad (1.3)$$

While, here, all the stations are assumed to abide the same maximum transmission power, this condition can be relaxed in favor a more general model in which  $p_i$  is bounded by  $p_i^{max}$ . If this model is to be utilized, the condition given in (1.2) should change to,

$$g_1 p_1^{max} > \dots > g_M p_M^{max}. \quad (1.4)$$

Although this generalization does exist, for notational convenience, throughout this report, we consider constant  $p_{max}$  for all the stations, unless specified otherwise.

At the chip level, the SIR is equal to the SNR. Therefore, with a background noise of  $I$ , the SIR for the  $i$ -th station becomes (see [47, 48] for more details),

$$\gamma_i = \frac{p_i g_i}{I + \sum_{j=1, j \neq i}^M p_j g_j}, \quad (1.5)$$

Hence, using Shannon's formula, the capacity of the  $i$ -th station becomes,

$$C_i = \log_2 (1 + \gamma_i) = \log_2 \frac{I + \sum_{j=1}^M p_j g_j}{I + \sum_{j=1, j \neq i}^M p_j g_j}. \quad (1.6)$$

Using (1.6) for computing the aggregate capacity of the system, we have,

$$C(\vec{\mathbf{p}}) = \log_2 \frac{\left( I + \sum_{j=1}^M p_j g_j \right)^M}{\prod_{i=1}^M \left( I + \sum_{j=1, j \neq i}^M p_j g_j \right)}. \quad (1.7)$$

Here,  $\vec{p} = (p_1, \dots, p_M)$  contains the decision variables of the optimization problem.

Using the definition of the goal function given in (1.7), the CSC uses the constraint given in (1.3) as well as two other ones, to be described here. The first constraint defines a minimum guaranteed SIR, as,

$$\gamma_i \geq \gamma, \forall i. \quad (1.8)$$

Furthermore, in the CSC, in order to suppress interference from one cell to the others, the aggregate received power at the base station is limited as,

$$\sum_{i=1}^M p_i g_i \leq P_{max}. \quad (1.9)$$

### 1.1.3 Fairness Analysis

The analysis of the fairness of the solution to the optimization problem introduced in Section 1.1.2 is an important issue in the problem dealt with here [29, 30]. Through imposing constraints specifically designed to control the range of the capacity offered to each station, the system can be made more fair. To do so, numerical measures for modeling fairness in the system are needed.

The subtractive unfairness of the system is defined as the difference between the highest and the lowest capacities offered in the system,

$$f = \max \{C_i\} - \min \{C_i\}. \quad (1.10)$$

Similarly, the ratio unfairness of the system is defined as the ratio between these two

capacities,

$$\tilde{f} = \frac{\max \{C_i\}}{\min \{C_i\}}. \quad (1.11)$$

Note that  $f$  and  $\tilde{f}$  are measures of fairness for the whole system. In contrast, as a station-specific measure of fairness, we define the capacity share of station  $i$  as,

$$\tilde{C}_i = \frac{C_i}{C}. \quad (1.12)$$

These measures will be used throughout this research in order to analyze the fairness of the solutions produced by different problems.

#### 1.1.4 System Parameters

In the model presented in Section 1.1.2, the parameters of each particular problem are the sequence of  $g_i$ s (denoted by  $\vec{g}$ ), as well as  $I$ ,  $\gamma$ ,  $p_{max}$ , and  $P_{max}$ , plus other parameters specific to each problem. In order to compare the effects of different parameters, a random sequence  $\vec{g}$  is produced, as described below. Then, to be able to compare the results for different values of  $M$ , while having a controlled variation, the sequence is down-sampled to produce new sequences with different lengths (to analyze the effect of the number of the stations). This way, it is possible to compare the effect of selecting different values of different parameters independent of the particular set of  $g_i$ s used at each instance.

Here, the work is carried out in a circular cell of radius  $R = 2.5Km$ . For the station  $i$  at the distance  $d_i$  from the base station only the path-loss is considered,

and modeled as [49] (for a comprehensive review of this subject refer to [50]),

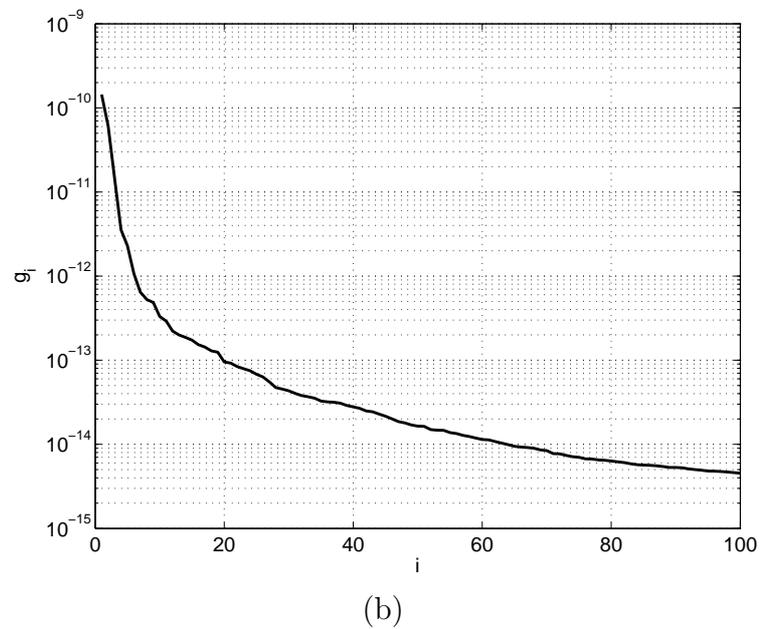
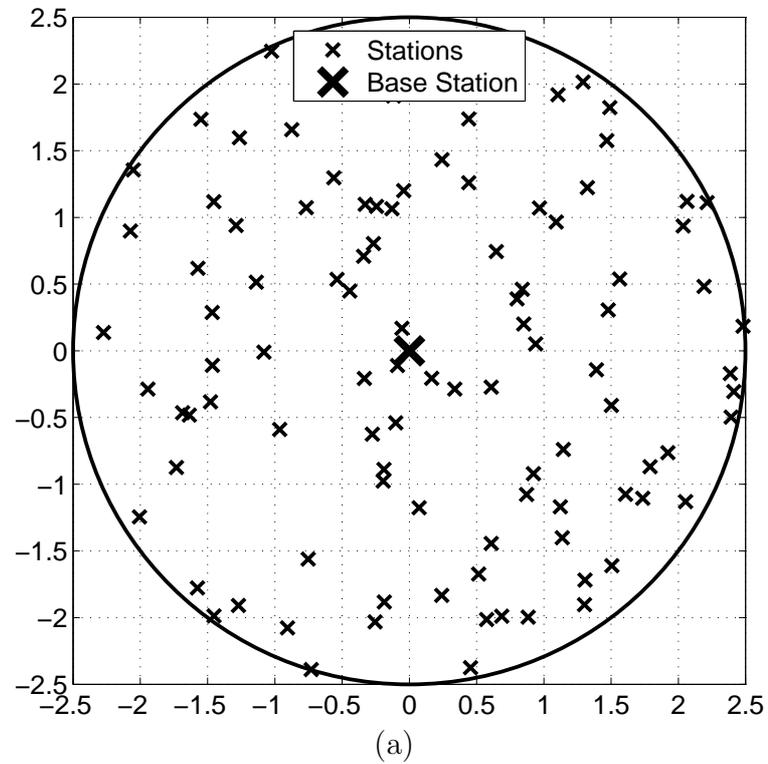
$$g_i = Cd_i^n. \quad (1.13)$$

Here,  $C$  and  $n$  are constants equal to  $7.75 \times 10^{-3}$  and  $-3.66$ , respectively, when  $d_i$  is in meters. Equivalently, with  $d_i$  in kilometers,  $C$  will equal  $1.2283 \times 10^{-13}$  [51] (also see [52, 53]). To produce a sequence  $\vec{g}$  of length  $M$ , a set of  $3M$  points are placed in the  $[-R, R] \times [-R, R]$  square, based on a two dimensional uniform distribution. Then, from those in the circle with radius  $R$  centered at the origin,  $M$  points are selected.

Figures 1.1-a and 1.1-b show the location of different stations and the sequence of reverse gains, respectively, in a sample set generated as described in the above. The surrounding circle in Figure 1.1-b shows the border of the cell.

The base parameters used in this study are  $\gamma = -30dB$ ,  $I = -113dBm$ ,  $P_{max} = -106dBm$ ,  $p_{max} = 23dBm$  ( $p_{max} = 30dBm$  is used in some other works [54]),  $M = 10$ ,  $\eta = 0.3$ ,  $\mu = \frac{1}{1.5}$ , and  $\alpha = 0.7$ . These values are partly based on the data given in [51, 52, 54, 55] (the parameters  $\eta$ ,  $\mu$ , and  $\alpha$  are defined in this work). Note that here the values of  $I$  and  $P_{max}$  comply with the notion of limiting the blocking probability, as defined in [56]. In any experiment, when a parameter is different from the list given in the above, it is mentioned. The conversion from  $dB$  to powers is performed according to  $xdB \equiv 10^{\frac{1}{20}x}$ . Also,  $xdBm \equiv 10^{\frac{1}{10}x}mw$ .

The execution times given here are measured on a PIV 3.00GHZ personal computer with 1GB of RAM, running Windows xp and MATLAB 7.0.



**Figure 1.1:** A sample cell. (a) Location of different stations in one cell. (b) Corresponding sequence of reverse gains.

## 1.2 Multiple-Cell Systems

Given that appropriate algorithms for solving single-cell problems exist, some of these methods could potentially be extended to multiple-cell systems.

An available model for noise aggregation in a multiple-cell systems suggests that the previous formulation could be reused [57], with the modification that the background noise to a station in a cell comes from the two sources of pure background noise and the signal received from all the stations in all the cells where the same frequency range is reused. Using an averaging method, which will assume the same level of out-of-cell interference hitting all the stations in one cell, the multiple-cell problem reduces to a set of inter-related single-cell problems [58]. More elaborate attempts for modeling multiple-cell systems are discussed in Section 1.2.1.

### 1.2.1 Literature Review

A major category of the research done on power optimization in multiple-cell systems approaches it from a game-theory perspective [51, 59, 60]. For example, in a recent paper [61] (an extension to the single-cell work by the same team in [62]), the authors aim at achieving a fixed SIR for all the stations through distributed calculation of the optimal transmission powers. To do so, a closed-loop control mechanism is designed which uses a linear combination of the transmission power and a capacity-related term as the cost function for each station. The capacity term in that paper is defined using the Shannon formulation, by assuming that the interference observed by any station is an independent Gaussian random variable. The paper partly adopts the definition of its cost from earlier works [44, 63].

A comprehensive study of the application of Game Theory-based methods adopted from the field of economics in multiple-cell power control is given in [63]. The aim of these methods is to set up an optimization process through which each station will independently maximize its own utility [63]. The definition of utility in this category is sometimes unique to each paper. The actual implementation of the game is different in different works as well. For example, in [64], the authors extend a centralized game-theory based approach to a decentralized one through implementing a penalty function which will encourage the stations to move towards the point in which every station meets its individually-assigned SIR while minimizing the overall interference to the neighboring cells. In [65] game-theory concepts are utilized for a joint analysis of the uplink and the downlink simultaneously, where fixed SIR is achieved in a multi-rate system.

The main theme of the game theory-based works cited in the above is the achievement of a fixed SIR for all the stations, and thus they are not directly applicable to this work. However, the schemes implemented in these works for extending single-cell methods to work in multiple-cell scenarios is helpful to this research. Especially, the decentralized schemes presented in works such as [64] are of great significance to this research. For example, in treating different updating methods, in [62], the approaches of parallel and random iterative updating of the transmission powers are discussed and it is mentioned that in a delay-free system, if all the stations have the same initial power level, the random update performs better than the parallel. For more work on multiple-cell fixed-SIR systems refer to [4, 40]. For more applications of methods borrowed from game theory and microeconomics refer to [66, 67, 68].

Aside from the updating strategy, there are at least two other important issues to deal with when working on the capacity-optimization problem in multiple-cell

systems. The first issue is the occurrences of hand-offs and how the model should treat them [61]. The other major issue is the fact that in some implementations, such as GSM for example, there could be delays of as long as  $500ms$  in the measurement and feedback loop [69]. The integrity and stability of the optimization method in these long-delay scenarios has to be carefully investigated.

The issue of base-station assignment is also a key factor in optimizing the capacity in a multiple-cell system [51]. Here we consider the case of each station being connected to only one base station chosen by a separate algorithm. Therefore, the aim of this work is to give an efficient method for optimizing the transmission powers assuming that the assignment is already given or that it will be optimized by an algorithm which uses the method developed here within an assignment-optimization procedure.

## 1.2.2 System Model

A schematic depiction of the multiple-cell model used in this research is given in Figure 1.2. This model is adopted from [61], which has in turn based its model on the ones given in [59, 64, 65]. A similar model is used in many other works, including [63].

Assume that there are  $K$  cells, with  $M_k$  stations in the  $k$ -th cell,  $k = 1, \dots, K$ . The  $i$ -th station in the  $k$ -th cell, where  $i = 1, \dots, M_k$ , transmits with the power  $p_{ki}$  and the path gain from this station to the base station at the  $j$ -th cell is denoted by  $g_{ki}^j$ . For convenience, we use  $g_{ki}$  when  $g_{ki}^k$  is referred to.

The background noise at the  $k$ -th cell is denoted by  $I_k$  and the chip-level signal to interference ratio of the signal transmitted by the  $i$ -th station at the  $k$ -th cell as

perceived by the base-station in this cell is modeled as,

$$\gamma_{ki} = \frac{p_{ki}g_{ki}}{I_k + \sum_{k'=1, k' \neq k}^K \sum_{i'=1}^{M_{k'}} p_{k'i'} g_{k'i'}^k + \sum_{i'=1, i' \neq i}^{M_k} p_{ki'} g_{ki'}} \quad (1.14)$$

It is helpful for dealing with (1.14) to define  $\tilde{I}_k$  as the extra background noise in cell  $k$  caused by neither the stations in this cell nor  $I_k$ , as,

$$\tilde{I}_k = \sum_{k'=1, k' \neq k}^K \sum_{i'=1}^{M_{k'}} p_{k'i'} g_{k'i'}^k. \quad (1.15)$$

In order to relate SIR to capacity, we use Shannon's theorem (see Section 1.1.2 for a detailed discussion) and write,

$$C_{ki} = \log_2(1 + \gamma_{ki}), \quad (1.16)$$

as the equivalent to (1.6) in multiple-cell systems. Using this model, the general multiple-cell capacity maximization problem dealt with in this research is composed as maximizing,

$$C = \sum_{k=1}^K \sum_{i=1}^{M_k} \alpha_{ki} C_{ki}, \alpha_{ki} > 0, \quad (1.17)$$

subject to,

$$\left\{ \begin{array}{l} \gamma_{ki} \geq \gamma_{ki}^{min}, \forall i, k, \\ C_{ki} \leq C_{ki}^{max}, \forall i, k, \\ \sum_{i=1}^{M_k} p_{ki} g_{ki} \leq P_k^{max}, \forall k, \\ 0 \leq p_{ki} \leq p_{ki}^{max}, \forall i, k. \end{array} \right. \quad (1.18)$$

Here, the constants  $\gamma_{ki}^{min}$ ,  $C_{ki}^{max}$ , and  $p_{ki}^{max}$  are the minimum SIR, the maximum capacity, and the maximum transmission power of the  $i$ -th station in the  $k$ -th cell, respectively, and  $\alpha_{ki}$  is the significance of this station to the system.

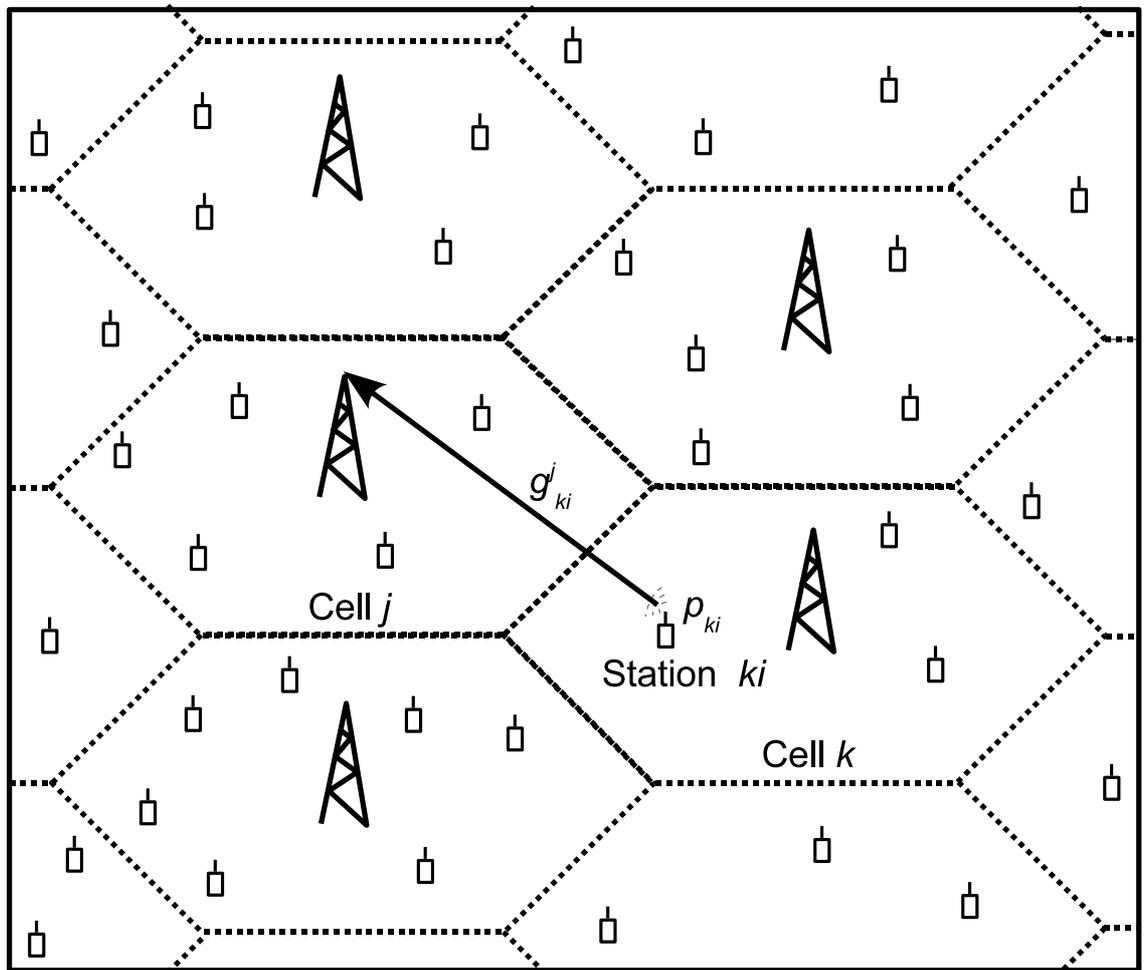


Figure 1.2: Multiple-cell system model used in this research.

# Chapter 2

## Summary of Results

This chapter contains a summary of the work done on the maximization of the capacity of the reverse link in CDMA systems through this research.

The focal point of this research is the optimization of the aggregate capacity of the reverse link in a CDMA system. The formulation and the model used in this research capitalize on previously published results which indicate that the dimension of the search space of the problem can be efficiently decreased. One of the main contributions of this research is that it eliminates the need for numerical search in most cases and yields closed-form solutions in many instances.

In the first stage, a new methodology is developed, based on which a closed-form solver algorithm is proposed for the existing problem, addresses as the classical problem in the text (CSC in short). Performance of the proposed solver for different sets of parameters is investigated and extensive computational cost analysis is given. It is shown that the proposed method is superior, both in terms of computational cost and precision of the solution. It is found out, however, that in compliance with

the available reports by other researchers, the solution to the CSC can potentially be vastly unfair towards the majority of the stations, for the benefit of one “elite” station.

In the next step, in order to deal with the issue of unfairness of the solution, a maximum capacity constraint is added to the problem. It is shown that the resulting problem, which is referred to as the NSC, is solvable by using the methodology developed for solving the CSC. Also, it is shown that the inclusion of this constraint increases the computational cost of the solver from  $O(M^2)$  to  $O(M^3)$ . Then, based on extensive experimental results, the performance of the NSC is analyzed and is compared with the CSC as well. The analysis contains cases of static systems, i.e. solving systems at a snapshot, and dynamic ones, i.e. solving a system iteratively as stations move around in a cell. It is observed that the CSC system does indeed separate the stations into all but one which are served at the minimum allowed capacity and one elite, the closest station, which is served with the most possible capacity feasible in the search space. On the contrary, the NSC is observed to distribute the resources evenly between stations and also to reasonably increase reliance on the stations as they get closer to the base station. Based on all the collected evidence, it is suggested that the incorporation of the maximum capacity into the problem leads to a more practical solution with an affordable increase in the computational cost. It is noted, however, that the favorable effects of the maximum capacity constraint on the fairness of system are indirect influences. Therefore, it is suggested that through more explicit control of system fairness better results could be achieved.

Following the line of research, in the next step, a maximum bound for the capacity share of the single stations is added to the NSC. This new constraint directly limits the

share of resources of the system used by each station, therefore inhibiting monopolies of capacity, as commonly observed in the results of the CSC. It is shown that the methodology developed for the CSC and used for the NSC are also applicable to the new problem, which is addressed as the N<sup>+</sup>SC for convenience. Through using an approximation, the effect of adding the new constraint on the performance of the solver is limited to doubling its computational cost, as opposed to increasing its order of complexity, as observed in the transition between the CSC and the NSC.

The solver proposed for the N<sup>+</sup>SC capitalizes on an approximation of the aggregate capacity. As the previously suggested algorithms the CSC and the NSC calculate the aggregate capacity for numerous candidate points, it is suggested that through extending the use of this approximation, reduction in the complexity of the previously proposed algorithms can be achieved. Before implementing these approximations, the error induced by the utilized approximations are analyzed and mathematical guarantees for the appropriateness of the application of the proposed approximation within the framework of the problem are given. Furthermore, it is shown that there is a decrease of one in orders of  $M$ , the number of the stations, in the computational costs of the available algorithms after the approximation is integrated into them. Using examples and numerous safety checks it is observed that beyond a negligible probability the solver is guaranteed to not generate false results induced by the error of the approximation. To calculate this probability, after running the exact algorithms alongside the ones which use the approximations, for an extensive number of randomly generated problems, the possibility of 5% error in the aggregate capacity being induced by the approximation is estimated to be less than 0.1%. Extensive investigation shows that this error happens in the case of the classical formulation of

the problem in which the system is capable of becoming very unfair. In fact, the approximation is shown to be vulnerable to monopoly of power. Hence, it is concluded that, in more controlled environments provided by the NSC and the N<sup>+</sup>SC, the approximation is capable of locating the exact solution with more than  $\frac{1}{5}M$  reduction in the computational cost (reduction of computational cost by an order of 10 for a 50-station cell).

In the steps summarized so far, it is assumed that the system operates based on the identity function, meaning the system benefits two times if the capacity offered to one stations is doubled. In practice, however, there is always a utility function which maps capacity to revenue or “interest of the operator”. Therefore, in the next step, the objective function is rewritten to calculate the sum of the utilities of the capacities. Then, it is shown that if the utility function is convex, the available algorithms work with minor modifications. Then, it is shown that in the case of a concave utility function, given that it meets a set of conditions, the stations should tend to make their transmission powers as close as possible to each other, to achieve a maximum aggregate capacity. This is in contrast with the case of identity and convex utility functions in which the stations try to make their transmission powers as far from each other as permitted by the constraints. It is argued that the unfairness of the solution to those problems is primarily a result of this tendency. As anticipated, empirical results show that concave utility functions lead to massively more fair outcomes than what is achieved by using convex functions. For problems which use concave utility functions, a solver is proposed which may use one-dimensional numerical search, in some cases depending on the values of system parameters. Nevertheless, the computational complexity of the solver is of second degree, in terms of the number of the

stations. It is proved that the algorithm locates the global maximum in all cases as well.

After analyzing the incorporation of general utility functions into the problem, the case of multiple-class systems is investigated. It is argued that in practical systems, service-providers tend to provide different classes of service, thus mandating different values of the constraints for each station, in the most general case. Analysis of this problem is intrinsically outside the scope of the methods available in the literature and the ones developed through this research as well. Therefore, the previously proposed approximation is utilized in order to yield first- and second-order approximations of the goal function. Then, using further approximations, the search space is reduced to a set of linear inequalities, thus paving the way for the use of linear and quadratic programming. While utilizing a second-degree approximation yields a more accurate outcome, the quadratic objective function overestimates the capacities and therefore may result in spurious results, because the aim of the problem is the maximization of the aggregate capacity. First-order approximation, on the other hand, is conservative but induces more error. Nevertheless, both algorithms are shown to be well inside a 5% error margin. The approximate algorithms solve a more general problem, at the cost of being computationally more demanding, due to the potential utilization of numerical optimization in them.

# Chapter 3

## Future Directions

In this chapter, directions for the continuation of this research are addressed. First, in Section 3.1, the potential developments of the problem in single-cell scenarios is discussed. Then, in Section 3.2, the implementation of the developed methods in multiple-cell systems will be discussed.

### 3.1 Single-Cell Systems

Extensions of the work accomplished on single-cell systems discussed here are primarily towards incorporating new features into the model and thus improving on the appropriateness of the corresponding solutions to real world problems. The first extension is presented in Section 3.1.1 where the incorporation of probability of activity as well as the characteristics between the spreading codes are discussed. The appropriateness of the approximations proposed in Section 3.1.1, subject to different values of the parameters, and the exact flow of the algorithm will be determined through

further research. It is also necessary to determine the range of system parameters which guarantee a bound on the induced error.

Material collected in Section 3.1.1 acts as the basis for the discussion given in Section 3.1.2 where the application of the developed methods in solving the problem of aggregate capacity maximization at symbol-level is investigated. Then, similar arguments are used for suggesting that the proposed methods can be utilized in the framework of a multiple-rate multiple-class system, in Section 3.1.3. Finally, in Section 3.1.4, the idea of using an approximation in order to broaden the range of utility functions implementable through the developed methods is introduced.

### 3.1.1 Incorporation of $\nu$ and $\alpha$

It is suggested that at any time each station is only active with the probability equal to  $\nu$ . Therefore, a more appropriate model for  $\gamma_i$ , originally defined in Equation (1.5), will be,

$$\gamma_i = \frac{p_i g_i}{I + \nu \sum_{j=1, j \neq i}^M p_j g_j}. \quad (3.1)$$

In [52], the value of 0.4 is suggested for  $\nu$  in voice systems. It is worth to mention that another method for modeling  $\nu$  is the assumption that a cell of  $M$  stations in fact includes  $M\nu$  stations [70], but in this research we will use the formulation given in (3.1) instead.

It is also suggested that a more accurate model for the SIR is to write,

$$\gamma_i = \frac{p_i g_i}{I + \alpha \sum_{j=1, j \neq i}^M p_j g_j}. \quad (3.2)$$

Here,  $\alpha$  is a constant depending on the characteristics between the spreading codes of stations. The value of  $\alpha = 1$  and  $\alpha = \frac{1}{3}$  for synchronous and asynchronous stations are suggested, respectively [29].

Through collective incorporation of (3.1) and (3.2) into the problem its accuracy could be increased. To do so, the SIR will be defined as,

$$\gamma_i = \frac{p_i g_i}{I + \alpha \nu \sum_{j=1, j \neq i}^M p_j g_j}. \quad (3.3)$$

The issue with the formulation given in (3.3) is that because of the existence of the factor  $\alpha \nu$ , the formulation given in (1.7) is not valid any more. This inhibits the use of the methodology which is based on analyzing the behavior of the problem in specific hyperplane, therefore the method developed for dealing the CSC will fail.

Nevertheless, using approximations, the problem can be transformed into one to which the constant- $T$  method, developed for the CSC, will be applicable. To do so, we define,

$$\chi = \frac{1}{\alpha \nu}, \quad (3.4)$$

$$\hat{I} = \chi I, \quad (3.5)$$

$$\hat{\gamma}_i = \frac{p_i g_i}{\hat{I} + \sum_{j=1, j \neq i}^M p_j g_j}, \quad (3.6)$$

$$\hat{C}_i = \log_2(1 + \hat{\gamma}_i), \quad (3.7)$$

$$\hat{P}_{max} = \frac{1}{\chi} P_{max}. \quad (3.8)$$

Note that in the presence of  $\chi$ , inequalities (1.3) and (1.8) will be intact, while (1.9) will be rewritten as,

$$\sum_{i=1}^M p_i g_i \leq \hat{P}_{max}. \quad (3.9)$$

Using (3.6), we know that,

$$\gamma_i = \chi \hat{\gamma}_i. \quad (3.10)$$

Here,  $\chi \gg 1$  with a nominal value of 7.5. Using proper approximations, it can be shown that,

$$C_i \simeq \chi \hat{C}_i. \quad (3.11)$$

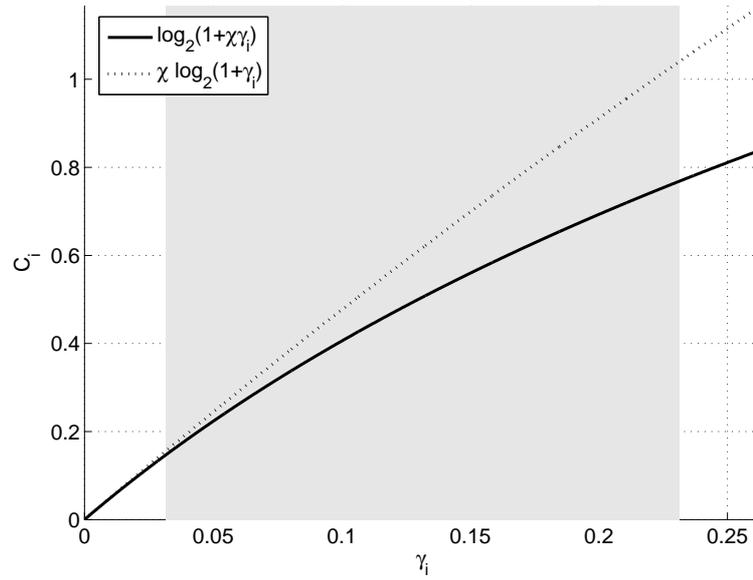
Therefore, in the existence of  $\alpha$  and  $\nu$ , proper approximations will transform the problem into one which is similar to the CSC.

Equation (3.11) is based on the series of approximations written as,

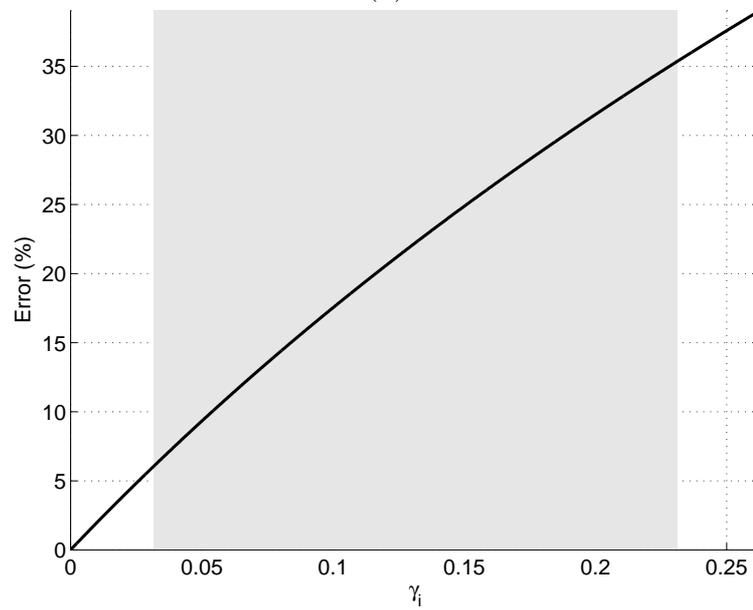
$$C_i = \log_2(1 + \chi \hat{\gamma}_i) \simeq \frac{1}{\ln 2} \chi \hat{\gamma}_i \simeq \chi \hat{C}_i. \quad (3.12)$$

Using value of  $\chi = 5$ , Figure 3.1–b shows that for  $\gamma_i \in [\gamma, 2^n - 1]$  (see Section 1.1.4) and  $\chi = 5$ , the error induced by the approximation could rise up to 35%.

In order to deal with the unacceptable error produced by the approximation given



(a)



(b)

**Figure 3.1:** Validity of the approximation given in (3.11) for  $\chi = 5$ .

in (3.11), we propose to use an enhanced formulation written as,

$$C_i \simeq \chi' \hat{C}_i. \quad (3.13)$$

Here,  $\chi'$  is not exactly equal to  $\chi$ , but is instead  $\chi$  multiplied by a factor less than one. As Figure 3.2 shows, for  $\chi = 5$ , using  $\chi' = 0.85\chi$  in fact cuts the error to almost a half. The determination of the best value of  $\chi'$  for any particular  $\chi$  demands more search.

It is also important to mention that while both (3.11) and (3.13) attempt at bringing  $\chi$  out of the logarithm, the next step will be the implementation of an approximation which will result in an approximate form of this problem in the classical framework. Therefore, it should be investigated further how the aggregate error induced by these two consecutive approximations could be managed through the implementation of one optimally designed approximation.

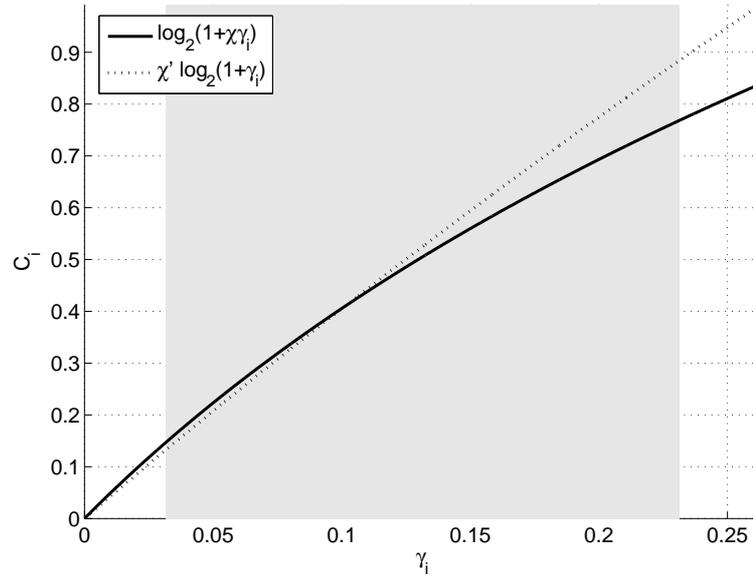
### 3.1.2 Symbol-Level Modeling

While the classical formulation for the SIR models the system at chip level, there is a straight-forward extension of this work to symbol level capacity optimization through writing [51, 59, 64],

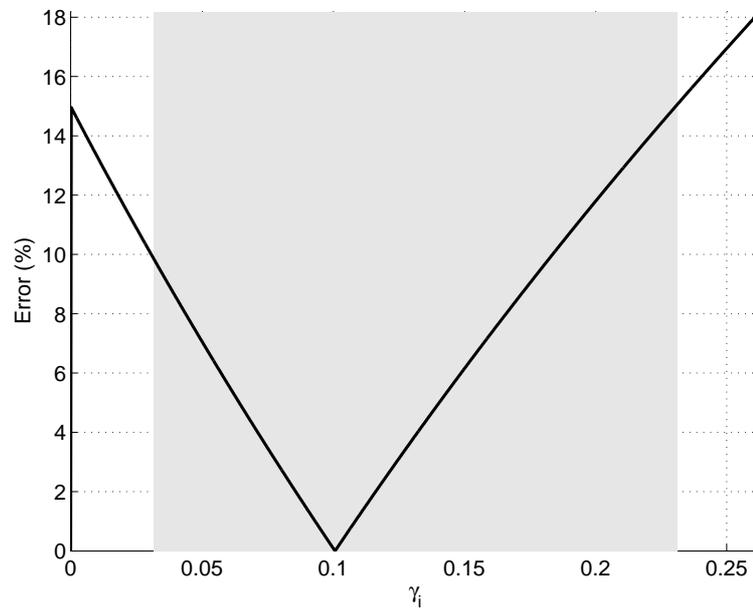
$$\gamma_i = \frac{L p_i g_i}{I + \sum_{j=1, j \neq i}^M p_j g_j}. \quad (3.14)$$

Here,

$$L = \frac{W}{R} > 1, \quad (3.15)$$



(a)



(b)

**Figure 3.2:** Validity of the approximation given in (3.13) for  $\chi = 5$  and  $\chi' = 0.85\chi$ .

is the spreading gain of the CDMA system, in which formulation  $W$  is the chip rate and  $R$  is the data rate. In order to rewrite (3.14) in a form which conforms to (1.5), we use an approach similar to the one taken in (3.6) by writing,

$$\hat{\gamma}_i = \frac{P_i g_i}{I + \sum_{j=1, j \neq i}^M P_j g_j}. \quad (3.16)$$

This way, Equations (3.7) and (3.11) are valid within a range of parameters and  $\chi$  will be equal to  $L$ .

In a typical system,  $W = 10^6 Hz$  and  $R = 10^4 bits/second$ , thus producing  $L = 100$ , which is well greater than 1 [54]. Using the notations developed in Section 3.1.1, here the problem yields  $\chi = 100$ , therefore threatening to cause unacceptable error values to be induced by the approximation. Further research is necessary on this topic.

### 3.1.3 Multiple-Rate Systems

The generalized formula given in (3.14) also considers the effects of data rate on the system and could be dealt with through using the approximation given in (3.6). Hence, using the method developed for solving the NSC, the work can be extended to multi-rate systems.

In doing so, the model is extended by assuming that the data-rate for the  $i$ -station is denoted by  $r_i$ . Therefore,

$$\gamma_i = \frac{L_i p_i g_i}{I + \sum_{j=1, j \neq i}^M P_j g_j}, \quad (3.17)$$

where,

$$L_i = \frac{W}{r_i}. \quad (3.18)$$

Hence, using the definition of  $\hat{\gamma}_i$  in (3.16), and considering the definition of the aggregate capacity, we have,

$$C_i \simeq \frac{W}{r_i} \hat{C}_i, \quad (3.19)$$

and therefore,

$$C \simeq W \sum_{i=1}^M \hat{\alpha}_i \hat{C}_i, \quad (3.20)$$

where,

$$\hat{\alpha}_i = \frac{\alpha_i}{r_i}. \quad (3.21)$$

Hence, given that the approximation does behave within an acceptable range of deviation, the problem can be rewritten as a single-rate multiple-class system by replacing  $\alpha_i$ s with  $\hat{\alpha}_i$ s, as defined in (3.21).

### 3.1.4 Approximating the Utility Functions

The incorporation of utility functions into the single-cell problem does rely on the existence of global bounds on the SIR and the maximum capacity. Moreover, that approach is not directly applicable to the case of multiple-cell systems. Nor could it work under the circumstances described in Section 3.1.1. However, the application of the set of approximations developed for dealing with single-cell multiple-class systems

can lead to a method capable of solving problems in which the utility function is not the identity function ( $f(x) \equiv x$ ).

Due to the fact that the approximations utilized in solving the M<sup>1</sup>SC and the M<sup>2</sup>SC capitalize on the first- and the second-order approximation of the capacity of one station, utility functions which could be accurately approximated by second-order terms could in fact be possible to incorporate into the problem, yielding another quadratic function with modified coefficients. If this approach succeeds, then a wider class of utility functions can be implementable through the use of the method developed for solving the M<sup>1</sup>SC and the M<sup>2</sup>SC. This method could also have applications in multiple-cell systems.

## 3.2 Multiple-Cell Systems

Following the detailed investigation of single-cell systems, as summarized in Chapter 2, the next major goal of this research is the analysis of multiple-cell systems. In reaching this goal, the most straight-forward approach is the iterative application of any of the developed single-cell methods on the individual cells through freezing the entire network except for one cell. This issue is discussed in Section 3.2.1. Another approach is the utilization of “virtual stations” for modeling a multiple-cell system as a set of quasi-independent single-cell systems. This issue is discussed in Section 3.2.2.

A more elaborate method for dealing with multiple-cell systems is the utilization of the reduction methods developed in the solver for the M<sup>1</sup>SC and the M<sup>2</sup>SC, which rewrote the aggregate capacity of the whole system as a linear or quadratic programming problem. This issue is discussed in Section 3.2.3.

### 3.2.1 Iterative Freeze-Update

In dealing with a multiple-cell system, as pictured in Section 1.2.2, the primary challenge is the existence of terms in the denominator of  $\gamma_{ki}$ . Collective address of these terms as  $\tilde{I}_k$  in the  $k$ -th cell, using (1.15), leads to rewriting (1.14) as,

$$\gamma_{ki} = \frac{p_{ki}g_{ki}}{\left[ I_k + \tilde{I}_k \right] + \sum_{i'=1, i' \neq i}^{M_k} p_{ki'}g_{ki'}}. \quad (3.22)$$

Dropping the redundant subscript  $k$  from (3.22) it will yield an equivalent of (1.5), namely the model for SIR used in single-cell systems.

In other words, by freezing all the cells except for one, the multiple-cell problem reduces to solving the single-cell problem in that particular cell. The iterative repetition of this technique could potentially result in a solution. This iterative algorithm, however, should be carefully analyzed for determining its dynamic stability. The appropriate choice of the updating method is also a point demanding more research (analysis of different updating methods has been carried out in different works, among which [56] deserves more attention due to the fact that its underlying problem is similar to the one discussed here).

### 3.2.2 Using Virtual Stations

In addition to the more accurate model for SIR presented in (1.14), there are approximate methods which directly reduce a multiple-cell system to an imaginary single-cell problem. For example, for modeling the interference coming from the stations in the

surrounding cells, it is suggested that we can rewrite (1.5) as,

$$\gamma_i = \frac{p_i g_i}{I + (1 + \delta) \sum_{j=1, j \neq i}^M p_j g_j}. \quad (3.23)$$

Here,  $\delta$  is the loading factor, also called the intercell interference factor (denoted by  $g$ ), and the values of 0.6 [70] or 0.55 [52] are suggested for it. Another conservative approximation for  $\delta$  is somewhere between 0.460 and 0.634 for nominal systems [71]. Equivalently, it is suggested that the intracell interference can be modeled as adding  $\delta M$  imaginary stations to a cell containing  $M$  stations [70].

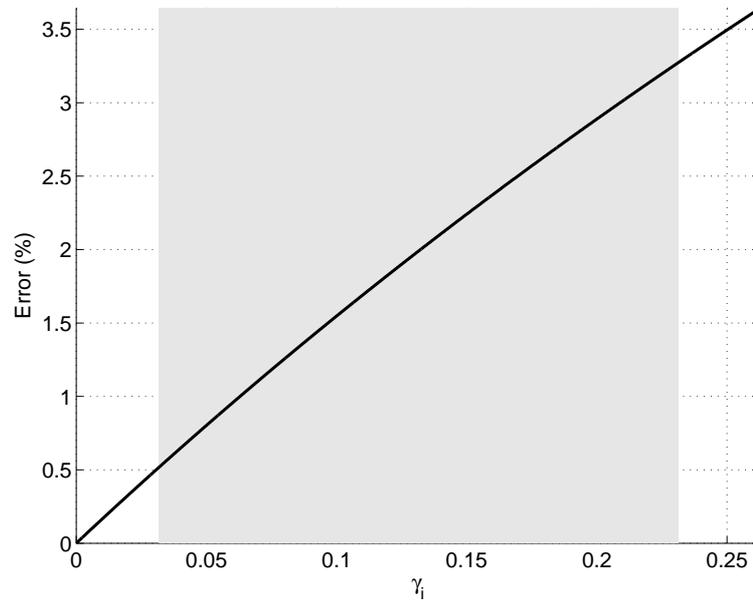
Using the approximate model for SIR given in (3.23) and capitalizing on the methodology proposed in Section 3.1.1 it is possible to rewrite the multiple-cell system, using appropriate approximations, in order to be able to integrate (3.23) into the method proposed for solving the CSC. To do so, defining  $\chi$  as,

$$\chi = \frac{1}{1 + \delta}, \quad (3.24)$$

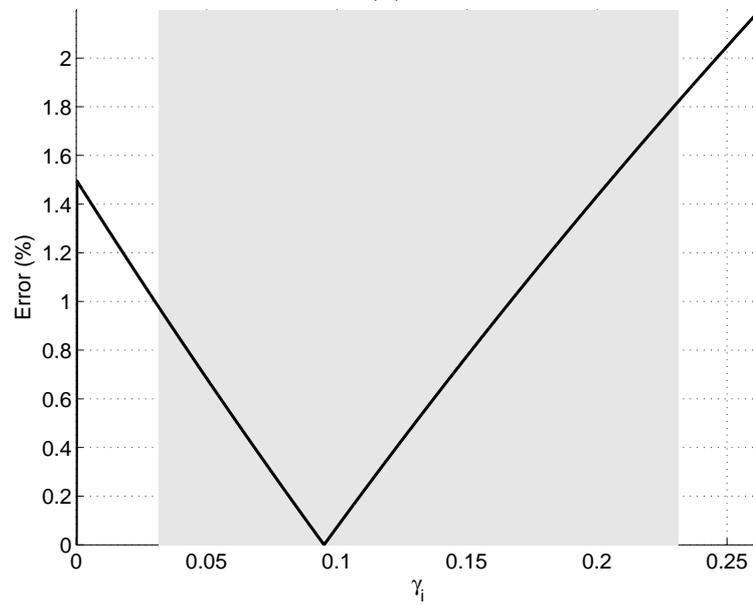
the approximation given in (3.11) could be utilized. It is worth to mention that here  $\chi < 1$ .

Figure 3.3 shows the case of  $\delta = 0.5$ . As seen in Figure 3.3-a, the approximation given in (3.11) generates less than 4% error. The case of using  $\chi'$ , formulated in (3.13), is presented in Figure 3.3-b showing that choosing  $\chi' = 0.1015\chi$  cuts the error in almost half.

It is also worth to mention that the model mentioned in Section 3.1.1 can also be



(a)



(b)

**Figure 3.3:** Validity of the approximations given in (3.11) and (3.13) for the case of (3.24) with  $\delta = 0.5$ . (a) The approximation given in (3.11). (b) The approximation given in (3.13) with  $\chi' = 0.1015\chi$ .

incorporated into this formulation, by setting,

$$\tilde{\chi} = \frac{1}{\alpha\nu(1+\delta)}. \quad (3.25)$$

Here, in fact, the more than one factor  $1 + \delta$  helps reduce the error originally caused by (3.4) due to generating a smaller  $\chi$ .

### 3.2.3 Reduction to Linear and Quadratic Systems

Analysis shows that first- and second-order approximation of the capacity of the single stations in terms of an intermediate variable is helpful in drastic reduction of the complicatedness of the analysis of the single-cell problem. It is also shown that these approximations are helpful in reducing the computational complexity of the solvers.

When dealing with multiple-cell problems, as given in Section 1.2.2, the formulation is not categorically different from the single-cell model when the multiple-cell problem is viewed as a set of interwoven single-cell problems. However, because the analysis given for solving the CSC is intrinsically capitalizing on the specific structure of the objective function, it is not directly applicable in multiple-cell scenarios. The replacement method developed in the M<sup>1</sup>SC and the M<sup>2</sup>SC, however, eliminates this high level of dependency to the structure of the objective function, as long as the approximations are utilized within the range. Moreover, the first- and second-order objective functions developed in the M<sup>1</sup>SC and the M<sup>2</sup>SC are still computationally affordable as the problems grows in size.

Therefore, it is anticipated that applying the approximations developed in dealing with the M<sup>1</sup>SC and the M<sup>2</sup>SC on the multiple-cell problem could generate linear or

quadratic problems which are indeed huge in size but still solvable. Note that this approach is intrinsically centralized and thus more research is needed to implement it inside a decentralized scheme.

# Chapter 4

## Publications

The material presented in this report has been previously published through these articles.

### 4.1 Conference Papers

- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, “A More Realistic Approach to Information–Theoretic Sum Capacity of Reverse Link CDMA Systems in a Single Cell”, In the IEEE International Conference on Communications (ICC 2007), Glasgow, Scotland.
- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, “Capacity–Share Controlled Information–Theoretic Sum Capacity of Reverse Link Single–Cell CDMA Systems”, In the 2007 IEEE 65th Vehicular Technology Conference, (VTC2007 Spring), Dublin, Ireland.

- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, “Information-Theoretic Sum Capacity of Reverse Link CDMA Systems in A Single Cell, An Optimization Perspective”, In the 8th Annual Conference for Canadian Queueing Theorists and Practitioners, CanQueue 2006, Banff, Calgary, Canada.
- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, “Closed Form Solution for QoS-Constrained Information-Theoretic Sum Capacity of Reverse Link CDMA Systems”, In the 2nd ACM Q2SWinet 2006, Torremolinos, Malaga, Spain.

## 4.2 Journal Papers

- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, “Approximation Algorithms For Maximizing The Information-Theoretic Sum Capacity of Reverse Link CDMA Systems”, *AEUE - International Journal of Electronics and Communications*, To Appear, 2007.
- Arash Abadpour, Attahiru Sule Alfa, and Anthony C.K. Soong, “Closed Form Solution for Maximizing the Sum Capacity of Reverse-Link CDMA System with Rate Constraints”, *IEEE Transactions on Wireless Communications*, Volume 7, Issue 4, April 2008, Pages:1179–1183.

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