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Optimal channel assignment and power control in wireless cellular networks

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OPTIMAL CHANNEL ASSIGNMENT AND POWER CONTROL IN WIRELESS CELLULAR NETWORKS

BY

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Abstract

Wireless mobile communication is a fast growing field in current telecommunication industry. In a wireless cellular network, channel assignment is a mechanism that assigns channels to mobile users in order to establish a communication between a mobile terminal and a base station. It is important to determine an optimal allocation of channels that makes effective use of channels and minimizes call-blocking and call-dropping probabilities. Another important issue, the power control, is a problem of determining an optimal allocation of power levels to transmitters such that the power consumption is minimized while signal quality is maintained. In wireless mobile networks, channels and transmitter powers are limited resources. Therefore, efficient utilization of both those resources can significantly increase the capacity of network.

In this thesis, we solve such optimizations by the hybrid channel assignment (HCA) method using integer linear programming (ILP). Two novel sets of ILP formulation are proposed for two different cases: Reuse Distance based HCA without power control, and Carrier-to-Interference Ratio based HCA combined with power control. For each of them, our experimental results show an improvement over other several approaches.

Dedication

To those who brightened me
To those who warmed me
To those who emboldened me
To the one who showed me the way
Thank you

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Table of Contents

List of Tables

List of Figures

1. Introduction

1.1. Mobile Communication

In recent years, due to the tremendous growth in the demand of communication services, there has been a great development in the area of communication technologies, especially, the wireless cellular networks.

In a cellular system, according to the cellular principle, a geographical area is partitioned into cells where each of them has a base station and contains a number of mobile terminals, for example, mobile phones. The base station is equipped with radio transmission and reception equipment, responsible for the communication between a mobile terminal and the rest of the network. A group of base stations are connected to the Mobile Switching Center (MSC), which connects the cellular network to other wired or wireless information networks.

To begin communication with a base station, a mobile terminal must obtain a channel from the base station, where a channel consists of a pair of frequencies: one frequency (the down-link) for transmission from the base station to the mobile terminal, and another frequency (the up-link) for the transmission in the reverse direction. The channel assignment problem deals with assigning an appropriate channel for each communication request, in another word, the new incoming call, that arrives in a cell. In order to mitigate radio frequency interference between channels, the selected channel must satisfy some electromagnetic compatibility constraints [1], also referred to as *hard* constraints, namely co-channel constraint (CCC), co-site constraint (CSC) and adjacent channel constraint (ACC).

Generally, channel assignment schemes are divided into three categories, fixed channel assignment (FCA), dynamic channel assignment (DCA) and hybrid channel assignment (HCA). In FCA, a fixed number of channels are assigned to each cell beforehand based on pre-estimated traffic load. In another hand, in DCA, channels are dynamically allocated based on incoming calls and the current network configuration. As a hybrid, HCA is a combination of FCA and DCA.

In addition to radio frequency, power of transmitters is another kind of scarce resources in mobile communications. The power control problem deals with assignment of an appropriate power level to the terminal at which the incoming call rises, with the objective of minimizing total power consumption and suppressing interference.

It is important to have a resource management scheme that can allocate these limited resources fairly and efficiently, but both the channel assignment and the power control problems, by themselves, are known to be difficult problems [2], [3]. Therefore, many researchers have traditionally considered these two problems separately [2], [4], [5]. For instance, first a channel is selected, and then a power control algorithm is used to check and update the carrier-to-interference ratio (CIR) value of the channel.

1.2. Problem Statement

In this thesis we present two sets of optimal integer linear programming (ILP) formulation (four formulations in total) that are used in the Hybrid Channel Assignment approach in wireless cellular networks. The first set of formulation does not consider power control; while the second set of formulation integrates channel assignment with power control. Our approach can also be easily applied to the Dynamic Channel Assignment problem as well.

For the channel assignment which does not cooperate with power management, many existing schemes solve a simplified version of the problem that only addresses the co-channel constraint [6], [7]. Our approach not only handles all three mandatory constraints, it also takes into consideration as well some optional conditions which are beneficial to the performance. The first formulation in this series does not involve reassignment of existing calls in the cell, while the second formulation allows such reassignment to further reduce the blocking probability.

When considering power control, in order to meet the required signal quality specifications, the assigned channel and its power level (for the incoming call) should be selected in a way that ensures that the CIR for the new call and all ongoing calls are maintained above an acceptable level. Existing techniques typically use heuristics to solve this problem, which generally leads to sup-optimal solutions. To improve this, we present the second set of formulations that can be used to optimally solve combined HCA and power control problem. They ensure that the CIR requirements are met, not only for the new incoming call but also for all ongoing calls using the same channel. This means that, unlike many previous approaches [8], [9], [10], the call dropping probability due to an incoming call is zero, because if CIR requirements can not be reached for all ongoing calls, then the new call is simply blocked. Furthermore, our approach specifies an appropriate power level to the incoming call and all ongoing calls using the selected channel such that the overall power consumption is minimized, leading to a significant reduction in blocking probability.

1.3. Contributions

Our contributions are summarized as follows.

1. A set of efficient Integer Linear Programming formulations for the optimization problem of channel assignment considering several kinds of radio interference constraints simultaneously, including co-channel constraint, co-site constraint and adjacent channel constraint.
2. An original, novel and efficient Integer Linear Programming approach to incorporate power control into channel assignment such that the call admission and power

resource management are fully integrated and are performed in one step, leading to a zero call dropping probability which is due to the entrance of an incoming call.

3. A set of efficient Integer Linear Programming formulations which guarantee that the selection of channels always meets the CIR requirements and optimal power is achieved.
4. Consider both non-reassignment and reassignment of channels, and compare their performances for our specific problem.

1.4. Organization of Thesis

In chapter 2, we give some background information in wireless mobile communication, such as system architecture, channel assignment, radio interference and power control. Chapter 3 describes our Integer Linear Programming methodology for the problem of finding an optimal channel assignment with and without power control, adopting channel reassignment and not. Chapter 4 addresses basic assumptions of the cellular model used in the simulation, as well as implementation details and experimental results. At last, chapter 5 concludes the dissertation and discusses future research directions.

2. Background Information

2.1. Cellular System Architecture

A typical cellular system architecture is illustrated in Figure 2.1. The covered geographical area is divided into many small service areas named cells [11]. In practical environment, the cell sizes are irregular and depend on the terrain and radio wave propagation conditions.

Each cell has a base station, associating with many mobile terminals, such as mobile phones, laptops and palms. The base station is usually placed in the center of a cell and has its own transmission capability with radio equipments. The mobile terminals communicate through wireless links with the base station located within the cell.

The base station provides an interface between the mobile units scattered across a cell and the Mobile Switching Center (MSC) which is also known as Mobile Telephone Switch Office (MTSO). The MSC plays as the central coordinating element for all cell sites, controlling call processing, handling billing activities, performing channel assignment, and providing necessary connection with other information networks, such as

Public Switching Telephone Network (PSTN). In short, the base station is responsible for the communication between mobile terminal and the rest of network.

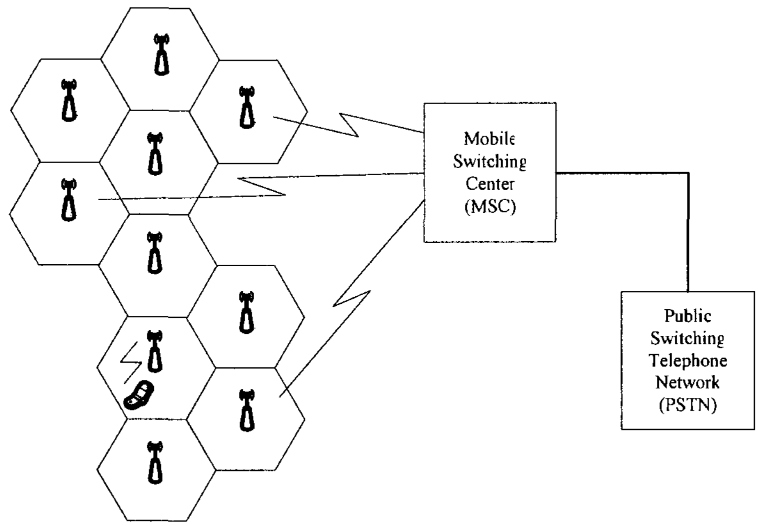

Figure 2.1: A typical cellular system architecture

A base station can communicate with mobile terminals as long as they are in its range of operation. The operating range depends upon the transmission power of the base station, and the radio energy dissipated per unit distance.

2.2. Communication Channel

When a call arrives in a particular cell, it will be assigned to a channel. A mobile user actually needs two channels: one for the mobile to base station link (or uplink), and another for the base station to mobile link (or downlink). As these two channels are assigned at the same time with the same manner, however, they are always taken as a single link in many studies. This ideal channel is considered as an ordinary communication resource, depending on the multiple access technique used by the cellular network. In practice, it could be a fixed radio frequency for a frequency division multiple access (FDMA), or a particular time slot within a frame for a time division multiple access (TDMA), or a specific code for a code division multiple access (CDMA) [11].

2.3. Channel Assignment

The capacity of a cellular system could be described in terms of the number of available channels, or, more effectively, the number of users that the system can support. The total number of channels available to the system is determined on the pre-allocated spectrum quota and the bandwidth of each channel. Since the number of available channels is limited while the number of mobile terminals is exponentially increasing, the channel must be reused as much as possible in order to increase the system capacity. This requires a proper channel assignment mechanism which involves allocating channels to cells or mobiles in a network efficiently, while satisfying the electromagnetic compatibility.

In general, channel assignment problems may be modeled as optimization problems which have the following form. Given a collection of radio terminals to be allocated operating channels, find an assignment that satisfies various constraints and minimizes the value of a given objective function. The work in [3] has shown that the assignment problem is NP-hard since it is equivalent to a generalized graph coloring problem.

2.3.1. Channel Reuse

As the reuse of channels is inevitable in a cellular system, channels used at one cell site may also be used at other cell sites in the case of absence of co-channel interference. Co-channel interference is radio interference caused due to the allocation of same channel to certain pairs of cells with geographical separation not enough to avoid deterioration of signal quality. The minimum distance required between the centers of two cells using the same channel to maintain the desired signal quality, is known as the reuse distance [7], [11], [12], [13], [14]. As shown in Figure 2.2, for example, if the reuse distance is 3, the cells in gray can not use the same channels occupied by cell x, because their distances to cell x are less than 3. Figure 2.3 shows a reuse pattern in which the cells with same number belong to the same reuse scheme and are free from co-channel interference, according to the reuse distance equal to 3. This reuse scheme is obtained by jumping from one cell to another in steps of length equal to the reuse distance [11], [15], [16].

The longer the reuse distance is, the smaller will be the co-channel interference level. However, a long reuse distance may result in lower reuse efficiency [15]. Thus, the frequency reuse scheme should be determined taking into consideration both the co-channel interference level and the reuse efficiency.

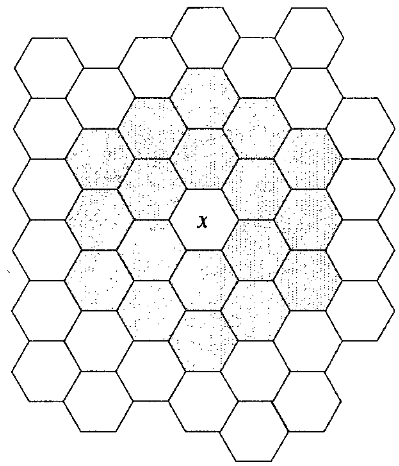

Figure 2.2: Reuse distance

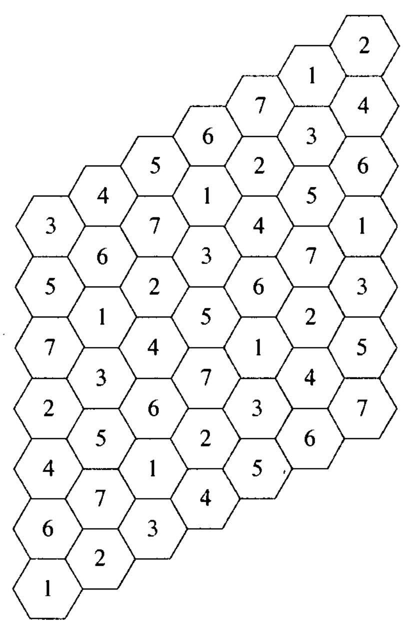

Figure 2.3: Reuse pattern (reuse distance is 3)

Traditionally, channel assignment is made according to the co-channel interference level determined by a fixed reuse distance which is decided during network planning. Many approaches proposed in literature to solve channel allocation problem are based on such concept [7], [11], [12], [13], [14], [15], [17], [18].

2.3.2. Channel Assignment Scheme

The channel assignment problem concerns allocating frequencies, for example, in a FDMA system, to mobile terminals and base stations such that the signal quality is guaranteed and network capacity is maximized. This is a difficult problem and has been widely investigated in literature. Various channel assignment schemes have been studied broadly to find better ways to assign channels to calls and to achieve higher level of channel reuse. Proposed schemes are mainly classified into two categories, Fixed Channel Assignment and Dynamic Channel Assignment.

In FCA, the set of channels are permanently allocated to each cell in advance according to the pre-estimated traffic intensity [18], [19], [20], [21], [22]. In a cell, a call can be assigned to a channel only if there is a free channel available in the predetermined set for this cell. Otherwise, the call might be rejected even though there are many channels available in the network.

In DCA, there is no permanent allocation of channels to cells. Instead, the whole set of available channels is accessible to all the cells, and the channels are assigned on a call-by-call basis in a dynamic manner [23], [24], [25], [28], [29], [30], [31]. Since a cell can use any of channels in a dynamic way, it is possible that if a cell uses all channels at a given time then there will not be any channel available to its neighboring cells at that time due to interference.

FCA scheme is simple but does not adapt to changing traffic load conditions and user distribution. Furthermore, the channel pre-allocation is difficult as it is based on the accurate knowledge of interference condition. These weaknesses are overcome by DCA. DCA makes cellular system more efficient in practice where the traffic load distribution is unknown beforehand or varies with time. The main advantages of DCA are the flexibility and the traffic adaptability, since channel assignment is made according to the current network conditions. DCA methods have better performance than FCA methods for light to medium traffic load [7], but it performs not so well under heavy load conditions. Furthermore, it requires more complex control and is relatively more time consuming [11].

Most of proposed DCA algorithms are heuristic based and do not guarantee an optimal solution. In addition, many existing DCA schemes consider a simplified problem with only co-channel constraint [23], [24], [25], [29], [30], [31], [32], [33]. Recently, DCA schemes for multi-hop wireless communications [40], [41], [42], [43] have also been proposed.

Many extensions and combinations of above two essential schemes have been studied in literature. The most basic are Hybrid Channel Assignment and Borrowing Channel Assignment (BCA).

The HCA [6], [7], [17], [44], [45] combines the features of both FCA and DCA techniques to overcome their drawbacks. In HCA, the set of channels is divided into two subsets [7], the Fixed Channel (FC) set in which channels are permanently allocated to given cells, and the Dynamic Channel (DC) set in which channels are available to all cells.

The ratio of the number of channels in each set is fixed a priori by the cellular network designer. For example, the representative ratios, FC:DC, for 70 channels in total, could be 35:35, 49:21 or 21:49. If FC is empty, then the HCA problem reduces to the classical DCA problem. When a new call arrives in a cell, the system first tries to serve it from the set of fixed channels. If no channel is available in the set of fixed channels, then the DCA scheme determines a suitable channel from the set of dynamic channels, satisfying the interference constraints and the traffic demands in cells.

In BCA [39], the channel assignment is initially fixed. When incoming calls arrive in a cell whose channels are all occupied, the cell borrows channels from its neighboring cells, and thus the call blocking is prevented [11].

2.3.3. Channel Assignment Constraints

Radio transmission in a channel may cause interference in other channels. Such interferences degrade the signal quality and hence the quality of service (QoS). In order to alleviate radio frequency interference between channels, the selected channel must satisfy the following electromagnetic compatibility constraints [1] which are also referred to as *hard* constraints.

1. *Co-channel constraint* (CCC)

   The same channel cannot be assigned to two cells that are separated by a distance less than a specified minimum reuse distance.

2. *Co-site constraint* (CSC)

Channels used in the same cell must be separated by a minimum amount, that is, their radio frequencies must be far enough apart.

3. *Adjacent channel constraint* (ACC)

Channels assigned to neighboring cells must be separated by a minimum amount.

In addition to the above *hard* constraints, there are a number of other conditions, which may be taken into consideration to improve the performance of the channel allocation technique. Such conditions are called *soft* constraints and could be violated if necessary [26]. They are described as follows.

1. *Packing condition*

Try to use the minimum number of channels every time a call arrives [11]. This condition encourages the selection of channels already in use in other cells as long as the hard constraints are satisfied.

2. *Resonance condition*

Try to assign the same channels to cells that belong to the same reuse scheme [11]. The purpose of this approach is to leave as many channels as possible to be allocated to other cells belonging to other reuse scheme. Consequently, the probability of causing co-channel interference in the system is reduced.

3. *Limiting rearrangement*

Try to assign, whenever possible, the same channels assigned before to the existing calls, thus limiting the reassignment of channels. Channel reassignment is the process of transferring an ongoing call to a new channel without call interruption [27]. Such reassignment in the entire cellular network upon the arrival of a new call will obviously result in lower call blocking probability, but it is complex both in terms of time and computation [11]. Therefore, the reassignment processes should be limited to a low level. On this account, limiting rearrangement condition is used to prevent excessive reassignment in a cell [11].

2.4. Power Control

To support communication, power must be supplied to transmitters. Owing to the scarcity of transmitter power, excessive use of power for transmission causes a faster drainage of power, resulting in short battery life. Furthermore, it will raise the interference to other users. In a wireless network, the signal quality is usually determined by Carrier-to-Interference Ratio (CIR), which is also known as Signal-to-Interference Ratio (SIR). Carrier represents the signal power received by a receiver from the transmitter in the cell where it is located, while interference represents the cumulative effect of signal powers from other transmitters using the same channel [7]. The signal quality and the level of interference in the wireless network depend upon the transmitter power levels.

Power control is a resource management process that is used to adjust transmission power such that the signal quality is maintained, while interference and power consumption are minimized. Due to its ability to suppress the co-channel and adjacent channel interference, power control can increase the network capacity.

Let us consider a situation under which a set of N transmitter-receiver pairs are using the same channel l. As mentioned before, the uplink and downlink, in another word, mobile-to-base frequency and base-to-mobile frequency, used by one communication are assumed not to interfere with each other and are allocated in the same manner. Here, in this thesis, we only consider the downlink frequency allocation. All the results in this thesis could be applied to the uplink easily. The relevant propagation effects are modeled by link gains, as illustrated in Figure 2.4. The link gain (actually power loss) from the transmitter of one link to the receiver of another link includes free space loss, multipath fading and other radio wave propagation effects [6].

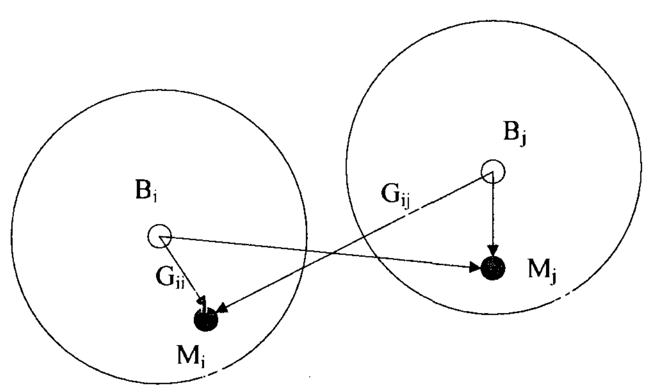

Figure 2.4: System geometry and link gains

Let B_j and M_j denote the base station and mobile terminal respectively in cell j, and let G_{ij} denote the link gain from the transmitter at B_j (for channel l), to the receiver at M_i

using the same channel in cell i. The gain G_{ii} corresponds to the desired communication link, whereas G_{ij} ($i \neq j$) corresponds to unwanted co-channel interferences. Let p_{jl} be the transmitter power on channel l at base station B_j. The signal power received at the receiver of M_i on the same channel, from the base station transmitter in cell j, is $G_{ij} \cdot p_{jl}$. The desired signal power at the receiver in cell i is equal to $G_{ii} \cdot p_{jl}$, while the total interfering signal power from other transmitters (using the same channel l for ongoing calls in their respective cells) to the receiver in cell i is $\sum_{j \neq i} G_{ij} \cdot p_{jl}$. As in [3], we use the CIR of M_i (denoted by Γ_i) as measure of the signal quality at mobile M_i.

$$\Gamma_i = \frac{G_{ii} \cdot p_{il}}{\sum_{j \neq i} G_{ij} \cdot p_{jl} + \eta_i} \qquad 1 \leq i, j \leq N \tag{2.1}$$

where η_i>0 is the thermal noise power at mobile M_i. The CIR is acceptable if Γ_i is above a certain threshold, γ_0, called the minimum protection ratio. This γ_0 reflects some minimum QoS that the link must support throughout the transmission in order to operate properly. Hence, for acceptable CIR, we have:

$$\frac{G_{ii} \cdot p_{il}}{\sum_{j \neq i} G_{ij} \cdot p_{jl} + \eta_i} \geq \gamma_0 \tag{2.2}$$

The objective of power control is to maintain the CIR requirements (2.2) for all ongoing and incoming calls.

Both power control schemes and DCA approaches are considered as the most efficient techniques to manage scarce resource available to the system [2], [4], [5], [34], [35], [36]. All the power control approaches presented can be described as centralized or distributed. Many researches demonstrated that a remarkable improvement in terms of spectrum efficiency and network capacity could be gained via integrating these two techniques together [36], [37], [38], but lots of them take an incompact way of integration, for example, finding proper channels firstly and then applying power adjustment to transmitters. Most existing PC-DCA algorithms such as those in [8], [9], [10], do not guarantee that all existing calls will maintain the desired CIR. Though the works in [4], [5] ensure that existing calls will not be dropped, they do not jointly optimize both channel allocation and power control.

3. Proposed ILP Methodology

3.1. General

Channel assignment schemes help to increase the network's capacity by efficiently distributing the channels across the network. Herein, we present our HCA approach whose details are briefly described as follows.

We assume each base station in a cellular network has a computer that stores the current state of its cell. The state of a cell includes information about channels, mobiles, and ongoing calls in such cell. Each base station sends its state to other base stations through a wired network between their computers. Channel assignment is made by the computer of the concerned base station according to the channel usage information stored in the allocation matrix. Letting C be the total number of cells in the network and L the total number of channels, the allocation matrix A is a binary matrix of size $C \times L$ such that

$$a_{i,j} = \begin{cases} 1 & \text{if channel } j \text{ is in use in cell } i, \\ 0 & \text{otherwise.} \end{cases}$$

The allocation matrix is updated every time a channel is allocated or released in the network, and each base station receives a copy of the allocation matrix. The total number of channels is divided into two sets, FC and DC. If FC is empty, then the problem reduces to the classical DCA problem.

Our HCA approach works like this. When a call arrives in a cell k at time t, we first search for a channel in the FC set that can serve the call. If no such channel is available from FC then we apply our ILP formulations on the DC set to obtain a best assignment of channels in cell k. The solution contains channels to be assigned to all ongoing calls in the cell k (ongoing calls maybe re-assigned new channels, for ILP2 and ILP4) and the channel to be assigned to the new call.

Following subsections address formulations which are used in above working frame.

3.2. HCA Strategy

In this part, we solve HCA problem based on reuse distance concept. Unlike most existing techniques, we consider all the three *hard* constraints, that is, co-channel, co-site and adjacent channel constraints, as well as the *soft* constraints. Our formulations are described as follows.

3.2.1. Notation (NT1)

In our ILP1 and ILP2 formulations, the symbols listed below are used to represent input data.

k : Cell where a call arrives.

d_k : Number of calls in cell k (traffic demand in cell k), including the new call.

r_0 : Reuse distance.

r_1 : Minimum distance between cells to avoid adjacent channel interferences.

g : Co-site interference channel interval.

w : Adjacent site interference channel interval, $g \geq w$.

C : Number of cells in the network.

L : Number of dynamic channels.

B : Set $\{1, 2, ..., L\}$ of channel numbers for all dynamic channels.

B_f : Subset of B, containing the channels currently not in use in cell k.

κ_i : Subset of B, containing the channels currently in use in cell i, $1 \leq i \leq C$.

$d_{i,j}$: Normalized distance between cell i and cell j, $1 \leq i, j \leq C$.

$res(i, j)$: A function defined as follows:

$$res(i,j) = \begin{cases} 1 & \text{if cell } i \text{ and cell } j \text{ belong to the same reuse scheme,} \\ 0 & \text{otherwise.} \end{cases}$$

$a_{i,j}$: An element of a $C \times L$ allocation matrix A, where each element, $a_{i,j}$, is defined as follows:

$$a_{i,j} = \begin{cases} 1 & \text{if channel } j \text{ is in use in cell } i, \\ 0 & \text{otherwise.} \end{cases}$$

W_1, W_2 and W_3 : Positive constants.

Two kinds of binary variables are also defined.

$$x_l = \begin{cases} 1 & \text{if channel } l \text{ is selected for the new call in cell } k, \ \forall\, l \in B_f, \\ 0 & \text{otherwise.} \end{cases}$$

$$y_m = \begin{cases} 1 & \text{if channel } m \in B \text{ is selected for an existing call or the new call in cell } k, \\ 0 & \text{otherwise.} \end{cases}$$

3.2.2. ILP without Channel Reassignment (ILP1)

We now present our first ILP formulation that allocates a free channel to a new call without any reassignment of existing channels. Using the notation given above, we formulate ILP1 as follows.

Objective function:

$$\textbf{Minimize} \quad -W_1 \sum_{i=1, i \neq k}^{C} \sum_{l \in B_f} \frac{a_{i,l} \cdot x_l}{d_{i,k}} + W_2 \sum_{i=1, i \neq k}^{C} \sum_{l \in B_f} a_{i,l} \cdot x_l \cdot (1 - res(i,k)) \qquad (3.1)$$

Subject to:

1. Constraint for one channel per call.

$$\sum_{l \in B_f} x_l = 1 \qquad (3.2)$$

2. Co-channel constraint.

$$x_l + a_{i,l} \leq 1, \ \forall l \in B_f, \ 1 \leq i \leq C, \ d_{i,k} < r_0, \ i \neq k \qquad (3.3)$$

3. Co-site constraint.

$$x_l + a_{k,q} \leq 1, \ \forall l \in B_f, \ \forall q \in B \setminus B_f, \ |l - q| < g \qquad (3.4)$$

4. Adjacent channel constraint.

$$x_l + a_{i,q} \leq 1, \ \forall l \in B_f, \ \forall q \in \kappa_i, \ 1 \leq i \leq C, \ i \neq k, \ d_{i,k} < r_1, \quad |l - q| < w, \ l \neq q \tag{3.5}$$

In our formulation, the traffic demand and *hard* constraints are handled by equations (3.2) - (3.5). There may be multiple channels that satisfy these constraints, but, among them, the objective function specified in (3.1) selects one channel that best meets the requirements of the *soft* constraints. W_1 and W_2 are positive constants and determine the relative significance of different terms. The first term expresses the packing condition. The objective value decreases if channel l is also in use in cell i which is free from co-channel interference with cell k. The decrease in the value depends upon the distance between the cells i and k. The second term expresses the resonance condition. The objective value decreases if channel l is also in use in cell i, and cells i and k belong to the same reuse scheme. Therefore, the objective function attempts to increase packing and assign the same channel to cells that belong to the same reuse scheme.

Constraint (3.2) ensures that each call is allocated exactly one channel from the pool of available dynamic channels that are currently not in use in cell k.

Constraint (3.3) enforces the co-channel constraint by ensuring that a channel $l \in B_f$ is not selected for a call in cell k if it is already in use in any neighboring cell i, assuming i and k are separated by a distance less than the reuse distance r_0.

Constraint (3.4) is the co-site constraint. It ensures that a channel l is selected in cell k only if it is separated by at least the co-site interval g, from any other channel q which is currently in use in cell k.

Constraint (3.5) states the adjacent channel constraint. It ensures that a channel l is selected in cell k only if it is separated by at least the adjacent channel interval w, from any other channel q, currently in use in a neighboring cell i, which is at a distance r_1. Normally, $g \geq w$ and $r_0 \geq r_1$.

3.2.3. ILP with Channel Reassignment (ILP2)

As mentioned before, channel reassignment, the process of transferring an ongoing call to a new channel without call interruption [27], can improve the QoS by lowering call blocking probability. Hence it is an important process in dynamic channel allocation. We now present our second ILP formulation that makes use of reassignment of existing channels. Using the notation given above, we formulate ILP2 as follows.

Objective function:

$$\textbf{Minimize} \quad -W_1 \sum_{i=1, i \neq k}^{C} \sum_{m \in B} \frac{a_{i,m} \cdot y_m}{d_{i,k}} + W_2 \sum_{i=1, i \neq k}^{C} \sum_{m \in B} a_{i,m} \cdot y_m \cdot (1 - res(i,k)) - W_3 \sum_{m \in B} a_{k,m} \cdot y_m \tag{3.6}$$

Subject to:

1. Constraint for one channel per call.

$$\sum_{m \in B} y_m = d_k \tag{3.7}$$

2. Co-channel constraint.

$$y_m + a_{i,m} \le 1, \ \forall m \in B, \ 1 \le i \le C, \ d_{i,k} < r_0, \ i \ne k \tag{3.8}$$

3. Co-site constraint.

$$y_m + y_p \le 1, \ \forall m, p \in B, \ |m - p| < g, \ m \ne p \tag{3.9}$$

4. Adjacent channel constraint.

$$y_m + a_{i,p} \le 1, \ \forall m, p \in B, \ |m - p| < w, \ 1 \le i \le C, \quad d_{i,k} < r_1, \ i \ne k \tag{3.10}$$

Equation (3.6) is the objective function. The first two terms are similar to those in ILP1. The third term expresses the limiting rearrangement condition. This term results in a decrease in the objective value if the new assignment for an ongoing call in the cell k is same as the previous allocation. Like in ILP1, W_1, W_2 and W_3 are positive constants and determine the significance of different terms.

Constraint (3.7) ensures that each call is allocated exactly one channel among all dynamic channels.

Constraint (3.8) enforces the co-channel constraint and is similar to constraint (3.3) except that, here, we consider every dynamic channel $m \in B$.

Constraint (3.9) is the co-site constraint. It ensures that two channels $m \in B$ and $p \in B$ are not selected in cell k if they do not have enough co-site interval g.

Constraint (3.10) is the adjacent channel constraint, similar to constraint (3.5). But here, we consider every dynamic channel $m, p \in B$.

3.3. HCA Integrated with Power Control

In this section, we solve the HCA and power control problem jointly by adopting CIR measurement concept which is based on Equation (2.2). For simplicity, we only take into account the co-channel interference. We leave co-site and adjacent channel constraints for future study.

The process of channel allocation is similar to that addressed before, but not the same. When a new call arrives in cell k, the computer of the concerned base station is not only responsible for allocating an available channel l to the call but also determining the transmitter power level to be used. The introduction of the new call may increase the interference levels in neighboring cells. Therefore, it is important that power levels of ongoing calls, using the same channel l allocated to the new call, are adjusted when necessary to ensure that the CIRs of ongoing calls do not fall below the specified threshold.

When no fixed channel is available for the incoming call, the ILP is used to find a proper channel in dynamic channels. Our ILP also evaluates whether any adjustment is needed to transmitter powers for the same channel in other cells, in order to maintain CIR of ongoing calls. If so, the ILP determines the lowest power levels for the selected channel in all cells, such that no ongoing calls will be dropped. The calculated power levels are then communicated to the respective base station computers in each cell. On receiving this information, the base stations update their power levels accordingly.

Unlike previous techniques, our approach jointly performs both channel allocation and power control, and adjusts power levels to guarantee no drop of ongoing calls.

We present our formations for HCA with power control in following subsections.

3.3.1. Notation (NT2)

In this series of formulations, we will use the following symbols to represent input data.

k	:	Cell where a call arrives.
d_k	:	Number of calls in cell k (traffic demand in cell k), including the new call.
M	:	Maximum transmission power level.
C	:	Number of cells in the network.
L	:	Number of dynamic channels.
B	:	Set $\{1, 2, ..., L\}$ of channel numbers for all dynamic channels.
B_f	:	Subset of B, containing the channels currently not in use in cell k.
$d_{i,j}$	:	Normalized distance between cell i and cell j, $1 \leq i, j \leq C$.
$G_{i,j}$	:	An element of a $C \times C$ gain matrix G, where each element, $G_{i,j}$, indicates the link gain between cells i and j.
$a_{i,j}$	:	An element of a $C \times L$ allocation matrix A, where each element, $a_{i,j}$, is defined as follows:

$$a_{i,j} = \begin{cases} 1 & \text{if channel } j \text{ is in use in cell } i, \\ 0 & \text{otherwise.} \end{cases}$$

We also define the following variables.

x_l, y_m : Binary variables defined as:

$$x_l = \begin{cases} 1 & \text{if channel } l \text{ is selected for the new call in cell } k, \ \forall\, l \in B_f, \\ 0 & \text{otherwise.} \end{cases}$$

$$y_m = \begin{cases} 1 & \text{if channel } m \in B \text{ is selected for an existing call or the new call in cell } k, \\ 0 & \text{otherwise.} \end{cases}$$

$p_{i,l}$: A continuous variable indicating the transmitter power level of channel l in cell i, $1 \le i \le C$.

3.3.2. ILP without Channel Reassignment (ILP3)

We now present our third ILP formulation that allocates a free channel to a new call without any reassignment of existing channels, such that the power is minimized. Using the notation given above, we formulate ILP3 as follows.

Objective function:

$$\textbf{Minimize} \quad \sum_{i=1}^{C} \sum_{l \in B_f} p_{i,l} \tag{3.11}$$

Subject to:

1. Constraint for one channel per call.

$$\sum_{l \in B_f} x_l = 1 \tag{3.12}$$

2. Constraint for assigning no power on idle channels.

$$p_{i,l} \le a_{i,l} \cdot M\,, \quad \forall l \in B_f\,, \quad 1 \le i \le C\,, \quad i \ne k \tag{3.13}$$

$$p_{i,l} \le x_l \cdot M\,, \quad \forall l \in B_f\,, \quad 1 \le i \le C \tag{3.14}$$

3. CIR requirements must be satisfied.

$$G_{i,i} \cdot p_{i,l} \geq \gamma_0 \cdot \sum_{j \neq i} G_{j,i} \cdot p_{j,l} + \gamma_0 \cdot \eta_i \cdot x_l, \quad \forall l \in B_f, \quad \forall i \ni a_{i,l} = 1 \cup \{k\} \tag{3.15}$$

The objective function specified in (3.11) selects an available channel l for the new call in cell k, such that the total transmission power required to maintain an acceptable CIR for the new call, as well as all existing calls on channel l, is minimized.

Constraint (3.12) ensures that the new call is allocated exactly one channel from the pool of available dynamic channels (B_f) that are currently not in use in cell k.

Constraint (3.13) states that, in all cells i ($i \neq k$), there is non-zero transmission power on channel l if and only if there is an ongoing call using that channel.

Constraint (3.14) states that power levels for all channels other than the channel l selected for the new call (i.e. the channel for which $x_l = 1$) is set to zero. We note that this does not imply that all transmitter power on the other channels is turned off. It simply means that for the purpose of calculating co-channel interference we are not interested in the power levels on other channels and those values will not be updated as a result of introducing the new call. The power levels calculated by the ILP only affect transmissions on the channel assigned to the new call.

Constraint (3.15) is based on Equation (2.2), and specifies that the desired signal level for communication using channel l, in a cell i must be at least γ_0 times the total co-channel interference plus the thermal noise power in the cell.

3.3.3. ILP with Channel Reassignment (ILP4)

Introducing channel reassignment, we present a reassignment-allowed version of ILP3, which allocates channels to the new coming call and all existing ongoing calls in the same cell, while the power is still minimized. Using the same notation, we formulate ILP4 as follows.

Objective function:

$$\textbf{Minimize} \quad \sum_{i=1}^{C} \sum_{m \in B} p_{i,m} \tag{3.16}$$

Subject to:

1. Constraint for one channel per call.

$$\sum_{m \in B} y_m = d_k \tag{3.17}$$

2. Constraint for assigning no power on idle channels.

$$p_{i,m} \le a_{i,m} \cdot M \,, \quad \forall m \in B, \; 1 \le i \le C, \; i \ne k \tag{3.18}$$

$$p_{i,m} \le y_m \cdot M \,, \quad \forall m \in B, \; 1 \le i \le C \tag{3.19}$$

3. CIR requirements must be satisfied.

$$G_{i,i} \cdot p_{i,m} \ge \gamma_0 \cdot \sum_{j \ne i} G_{j,i} \cdot p_{j,m} + \gamma_0 \cdot \eta_i \cdot y_m \,, \quad \forall m \in B, \quad \forall i \ni a_{i,m} = 1 \cup \{k\} \tag{3.20}$$

The objective function specified in (3.16) selects a set of available channels for the new call and other ongoing calls in cell *k*, such that the total transmission power required for all transmitters using channel *l* is minimized.

Constraint (3.17) guarantees that every call is allocated exactly one channel from the pool of all dynamic channels (B) in cell k.

Constraints (3.18) - (3.20) have analogous purposes of (3.13) - (3.15), respectively. But here, (3.19) is supposed to force power levels for all channels which are not selected (i.e. the channels for which $y_m = 0$) to be set to zero.

4. Simulation and Results

We conduct simulations to examine our proposed ILP approach. In literature, several indicators are used to evaluate the performance of a channel assignment scheme, such as call blocking/dropping probability, bandwidth utilization and channel acquisition delay [15]. In this thesis, since our proposed HCA scheme will not cause any call dropping, the performance of the channel allocation scheme at a particular traffic load is assessed by measuring the call blocking probability. It is the ratio between the number of coming calls blocked and the total number of calls arriving in the system.

In following sections, after addressing the cellular model assumptions and traffic model used in our simulation, we discuss the experimental results.

4.1. Cellular Model Assumptions

In this thesis, our ILP approach is applied to the mobile cellular model proposed in [26] which is also used in [12]. The basic characteristics of the model are briefly summarized as follows.

1. The topological model is a group of hexagonal cells that forms a parallelogram shape (equal number of cells along x-axis and y-axis) as shown in Figure 4.1 [7]. The wireless network used for simulation consists of 49 cells.

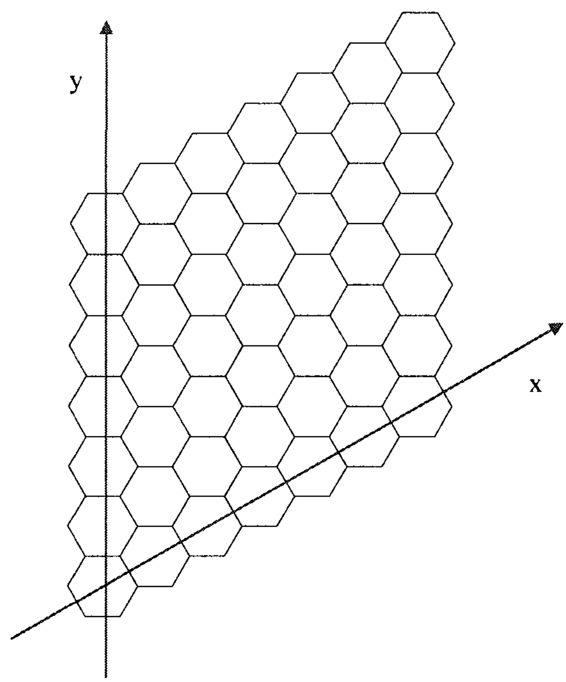

Figure 4.1: Cellular topological model

2. The total number of channels for the network is 70, divided into two parts, FC and DC, that is, $|FC \cup DC| = 70$. Each channel may serve only one call. In FCA, the available fixed channels are distributed among the cells; while in DCA, all dynamic channels are put in a central pool. A channel is assigned to an incoming call by a central controller that monitors the whole cellular network.
3. Incoming calls at each cell may be served by any of the available channels.
4. The selection of a channel is subject to co-channel, co-site and adjacent channel

interference, for ILP1 and ILP2. And for ILP3 and ILP4, it is only subject to the co-channel interference, based on CIR measurement.

5. The basic object of the network model is the link, that is, a communication between a base station and a mobile through a channel.
6. A new call at cell k is blocked if neither fixed channel nor dynamic channel is available to satisfy the electromagnetic interference constraint.
7. Existing calls in a cell involved in a new call arrival may be reassigned new channels (ILP2 and ILP4 only).

With these model assumptions, we can compare our results with those obtained by other works.

4.2. Traffic Model

In our simulation, we assume the traffic model to follow the blocked-calls-cleared queuing discipline. An incoming call is served immediately if a channel is available; otherwise the new call is blocked and not queued. The most fundamental characteristics of this model include: infinite number of users, finite number of channels for the network, no queue for new calls, call arrival follows a Poisson process with mean arrival rate of λ calls/hour. And the call duration is a random variable with exponential distribution of the form:

$$f(x) = \begin{cases} b \exp^{-bx}, & x \geq 0 \\ 0, & x < 0 \end{cases} \qquad (4.1)$$

where b is the mean duration time of calls [11]. Inter-arrival time follows a negative exponential distribution with mean b. The product of the mean arrival rate and the mean call duration gives the traffic load imposed to the cellular network model.

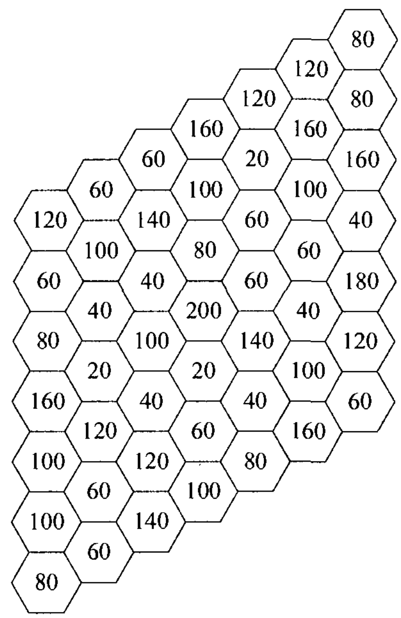

Figure 4.2: Non-uniform traffic distribution pattern 1 with initial arrival rates

The traffic in the cellular network may either follow uniform or non-uniform distribution. In uniform traffic distribution, every cell has the same traffic load. While in non-uniform traffic distribution, the call arrival rates are different in cells. Two typical traffic patterns used in [11] are illustrated in Figure 4.2 and Figure 4.3. The number in a cell represents the mean call arrival rate per hour, under normal load condition. In this thesis we use Pattern 1 for simulation, and for the mean call duration, we set it to 180 seconds.

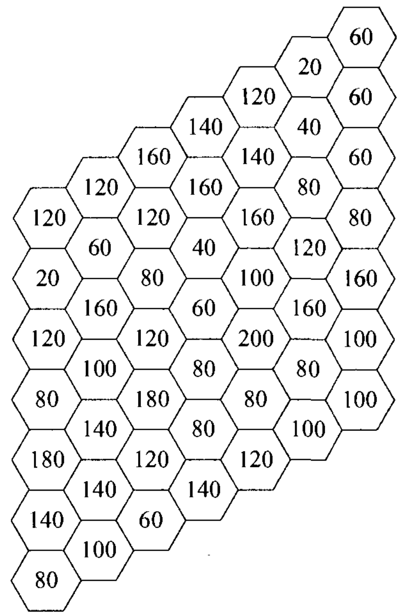

Figure 4.3: Non-uniform traffic distribution pattern 2 with initial arrival rates

4.3. Implementation Details

The simulation was implemented in Java programming language using Eclipse 3.2.2 Integrated Development Environment. The platform is SunOS 5.10 with Java Runtime Environment 1.5. ILOG CPLEX 11.1 is used as the engine for solving ILP problems. This section describes some details in the simulation.

4.3.1. Processing Call Event

Based on given call arrival rate in each cell and the mean call duration, a list of calls is generated, in which each record consists of the information about a call, including its ID number, the cell involved in call arrival, the clock of the time when this call arrival occurs, and the duration of this call. Obviously, the clock of the time when a specific call is released can be calculated. Such call arrival and call release are referred to as call events.

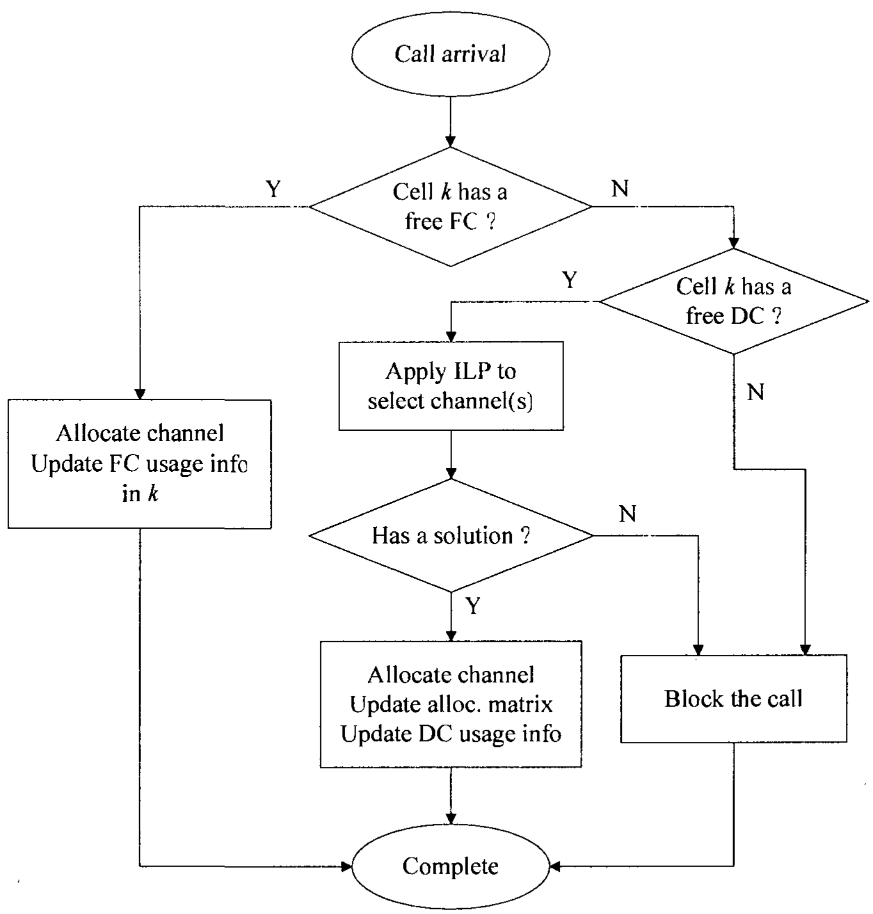

Figure 4.4: Processing call arrival event

All the call events of calls are put together and sorted in terms of the clock of occurrence, and then processed by the simulator one after another. After processing each event, the channel usage information of the cell involved in call arrival is updated. To measure the system performance, the numbers of new incoming calls and calls blocked in the system are recorded. Figure 4.4 shows the flowchart of processing call arrival event, and Figure 4.5 illustrates flowchart of processing call release event.

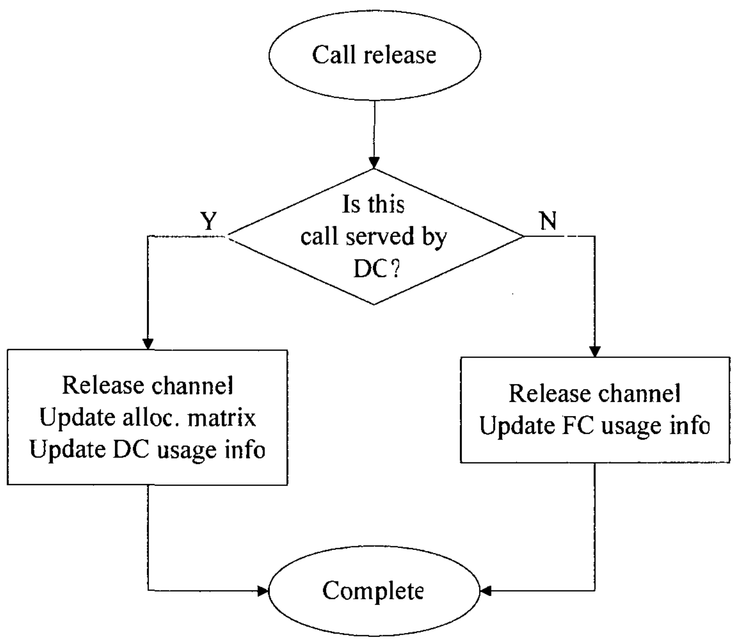

Figure 4.5: Processing call release event

4.3.2. Determination of Allocation Matrix

The allocation matrix A is used to record the usage of dynamic channels in the whole cellular system, hence itself is also dynamic. It is updated every time a call is successfully assigned a dynamic channel and when an ongoing call is released. Before the start of simulations, A is initialized with zeros.

4.3.3. Determination of Distance between Cells

As described in [15], the distance between two cells is a Manhattan distance. The distance between any two cells is the minimum number of steps needed to move from one cell to another. A step is the distance between the centers of two adjacent cells, and is considered as the unit distance. That is, it has value of 1. For instance, as shown in Figure 4.6, the minimum number of steps required to go from cell *a* to cell *b* is 5, so the distance is 5; while the distance between cell *c* and *d* is 3.

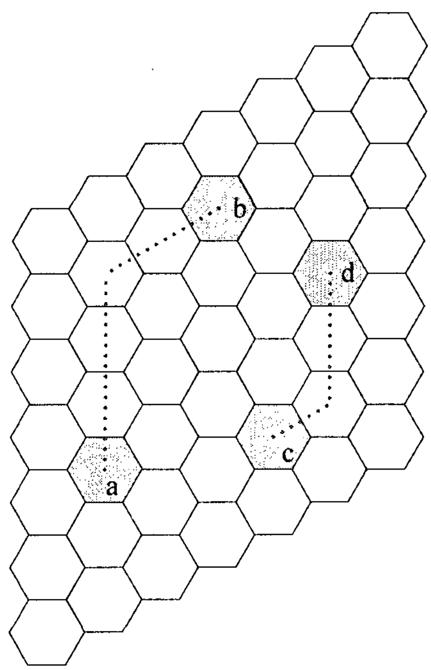

Figure 4.6: Distance between two cells

4.3.4. Determination of Link Gain Matrix

As mentioned in section 2.4, link gain includes free space loss, multipath fading and other radio propagation effects. It depends upon the particular propagation model of the channel [4]. We herein assume that all link gains are affected by shadow fading only. The signal strength is assumed to decrease with the second power of the distance. The element, $G_{i,j}$, of link gain matrix G is given by $G_{i,j} = \frac{1}{d_{i,j}^{2}}$, where $d_{i,j}$ is the distance between the mobile i and base station j.

4.4. Experimental Results

In our simulations, similar to the works in [7], we used three representative ratios of fixed and dynamic channels, FC:DC: 21:49, 35:35 and 49:21. The performance of the ILP formulations is derived in terms of blocking probability for new incoming calls.

For formulation ILP1 and ILP2, the initial load in each cell was set to 60% of the normal load and the results were obtained by increasing the traffic rates by 33% for all cells. The reuse distance, r_0, is set to 3. We also set W_1=1.5, W_2=2 and W_3=1, which were determined by trial-and-error. For formulation ILP3 and ILP4, we set η_i, the thermal noise received by each receiver, to $1/10^5$.

			Percentage increase of traffic load						
FC:DC	*g*	*w*	0	33	66	100	133	166	200
21:49	1	1	0.00	0.00	0.01	0.04	0.10	0.14	0.19
	2	2	0.00	0.05	0.10	0.18	0.26	0.30	0.35
	3	2	0.01	0.08	0.14	0.22	0.31	0.34	0.40
	3	3	0.06	0.16	0.24	0.32	0.39	0.44	0.48
35:35	1	1	0.00	0.00	0.03	0.09	0.17	0.21	0.26
	2	2	0.01	0.07	0.14	0.21	0.29	0.34	0.39
	3	2	0.02	0.10	0.18	0.26	0.33	0.37	0.43
	3	3	0.06	0.18	0.26	0.33	0.41	0.44	0.49
49:21	1	1	0.00	0.04	0.10	0.18	0.26	0.30	0.36
	2	2	0.03	0.12	0.20	0.27	0.35	0.39	0.45
	3	2	0.05	0.14	0.23	0.30	0.38	0.42	0.47
	3	3	0.09	0.19	0.27	0.35	0.42	0.46	0.51

Table 4.1: Blocking probabilities of ILP1

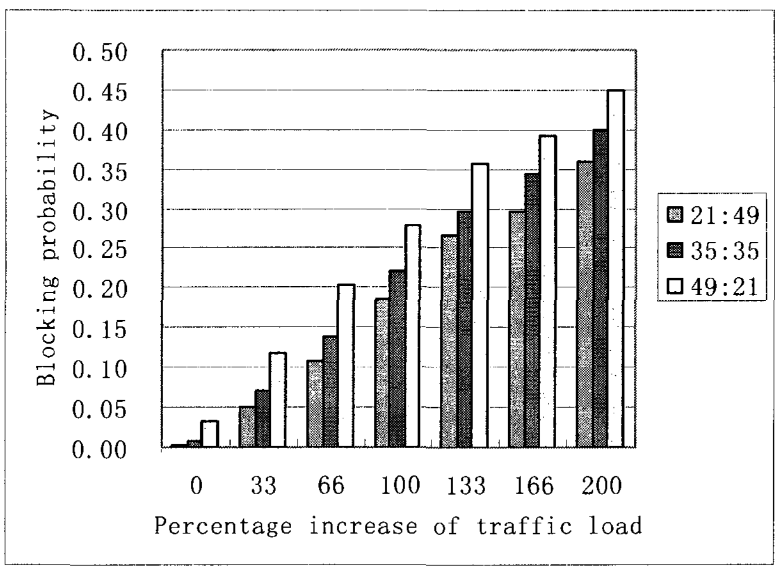

Figure 4.7: Blocking probabilities of ILP2 for g=2 and w=2

Table 4.1 shows the blocking probabilities for channel allocation without any reassignment of existing calls (obtained using ILP1). As expected, the blocking probability increases with increasing traffic load on the network, and with the required channel interval for co-site constraint (g) and adjacent channel constraint (w). But the network performs better as the number of dynamic channels increases. This was expected as the higher number of dynamic channels means that the scheme has more freedom and can choose channels from a larger set to assign to calls.

We have tested ILP2, where channel reassignment is allowed, with different combinations for the values of g and w, each ranging from 1 to 4. Figure 4.7 shows the blocking probabilities when $g = 2$ and $w = 2$. Results with other values of g and w are similar. As before, blocking probability increases with traffic, and also with required channel intervals for co-site and adjacent channel constraints. However, as shown in the figure, the 21:49 ratio consistently gives the best performance, followed by 35:35 and 49:21.

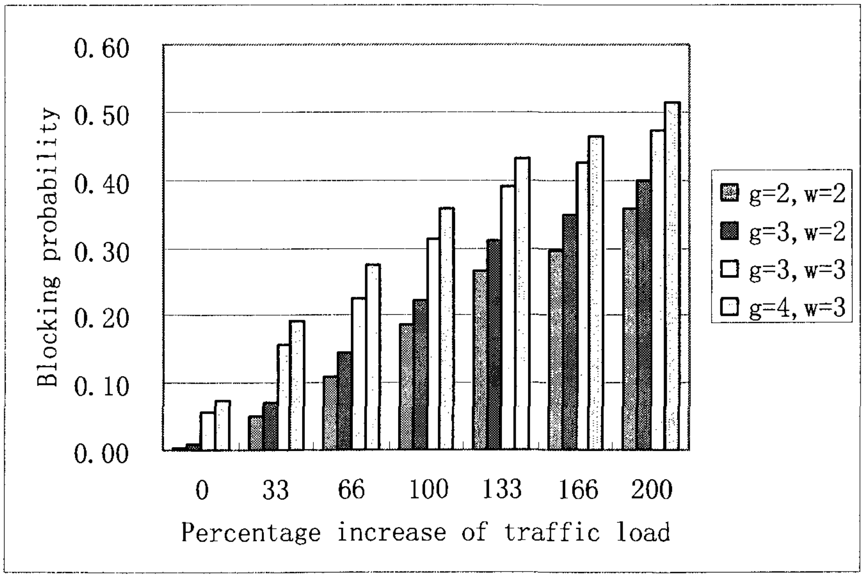

Figure 4.8: Performances of ILP2 for ratio 21:49

Figure 4.8 shows how the blocking probabilities are affected by the requirement of different values of co-site and adjacent channel intervals, for the ratio 21:49, under reassignment scheme. We see that even small changes in the values of g and w can have a significant effect on the blocking probability. The results for the 35:35 and 49:21 ratios followed a similar pattern, but the overall blocking probabilities were higher.

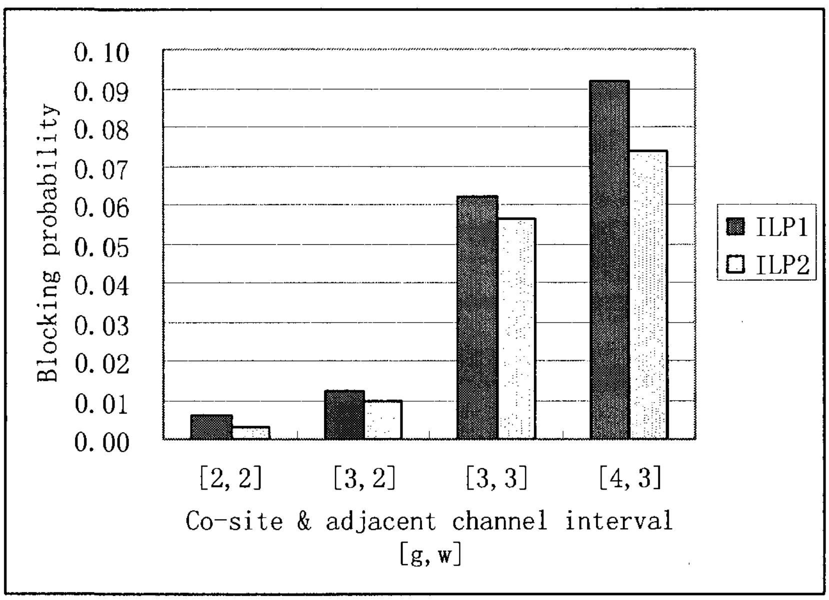

Figure 4.9: Performances of ILP1 vs. ILP2 for ratio 21:49 with initial traffic load

Figure 4.9 shows the comparison between reassignment and non-reassignment, for the ratio 21:49 (results with other ratios are similar). Our results indicate that although channel reassignment does reduce blocking probability, the amount of improvement seems to vary with traffic load and the values for g and w. We are conducting further experiments to determine the conditions under which channel reassignment is most beneficial.

		Percentage increase of traffic load						
FC:DC	Scheme	0	20	40	60	80	100	120
21:49	ES	0.00	0.00	0.01	0.02	0.07	0.14	0.17
	ILP1	0.00	0.00	0.04	0.06	0.11	0.17	0.19
35:35	ES	0.00	0.00	0.01	0.03	0.08	0.14	0.17
	ILP1	0.00	0.00	0.03	0.05	0.11	0.16	0.19
49:21	ES	0.00	0.00	0.03	0.05	0.10	0.16	0.19
	ILP1	0.00	0.01	0.05	0.07	0.12	0.18	0.21

Table 4.2: Comparison of performances with ILP1 and the ES approach in [7]

We also have compared our approach with the evolutionary strategy (ES) based HCA scheme proposed in [7], which considers co-channel constraints only. We simulate this by setting $g = 1$ and $w = 1$ in our formulation. Initial traffic in each cell, percentage increase of load and other parameters including the values of W_1 and W_2 were set to the same as in [7]. Table 4.2 compares the results, where the rows "ES" and "ILP1" indicate the blocking probabilities in [7] and our ILP1, respectively, under different traffic loads. As shown in this table, our results without channel reassignment are similar to those in [7] with channel reassignment.

The formulations for HCA integrated with power control, namely ILP3 and ILP4, make channel selections only according to co-channel interference.

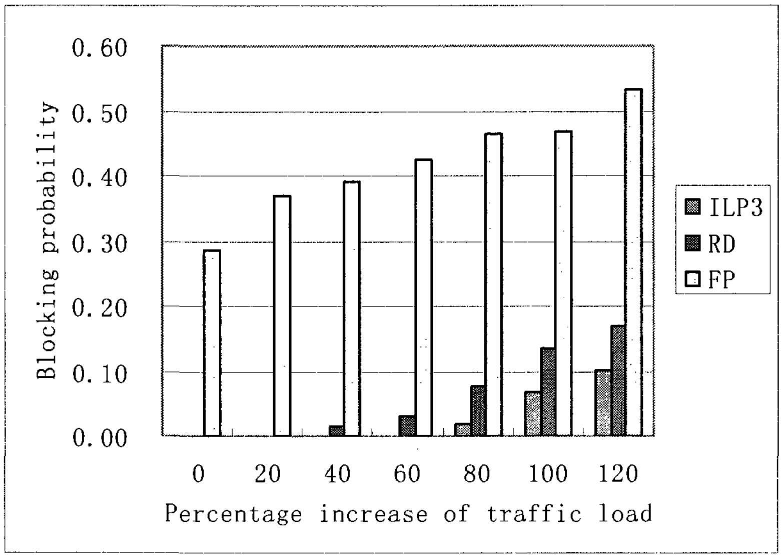

Figure 4.10: Blocking probabilities of ILP3 for ratio 21:49 with CIR=2

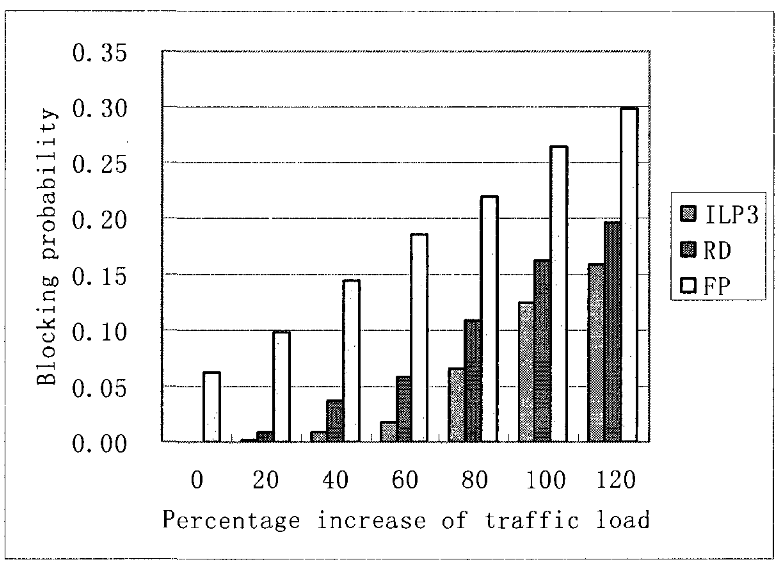

Figure 4.11: Blocking probabilities of ILP3 for ratio 49:21 with CIR=2

Figure 4.10 (and Figure 4.11) compares the blocking probabilities obtained using our proposed ILP3 with those obtained using a reuse distance based technique (labeled by RD) [7], and those considering fixed power level (labeled by FP), for the case of FC:DC = 21:49 (and 49:21). We note that the proposed ILP3 clearly results in reducing the blocking probability, by decreasing co-channel interference at the receivers. The case of FC:DC = 35:35 follows the same pattern. For above simulations, we set CIR to 2 and reuse distance to 3. These two parameters can be considered "equivalent" in the sense that in both cases a single channel can accommodate approximately 8-9 calls simultaneously in the entire network.

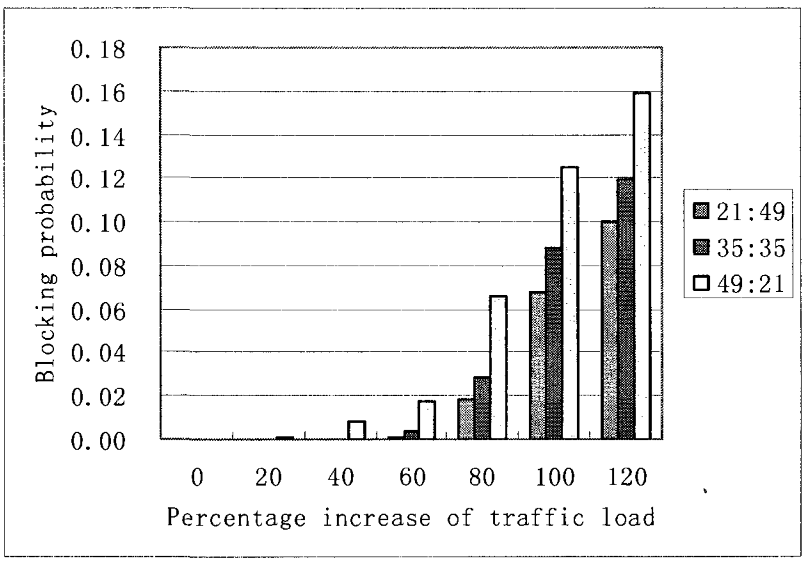

Figure 4.12: Comparison of different FC:DC ratios with CIR=2 for ILP3

Figure 4.12 compares the relative performance of the different ratios of FC:DC, using the proposed ILP3 for CIR=2. As expected, blocking probability increases with traffic, and the 21:49 ratio consistently gives the best performance, followed by 35:35 and 49:21.

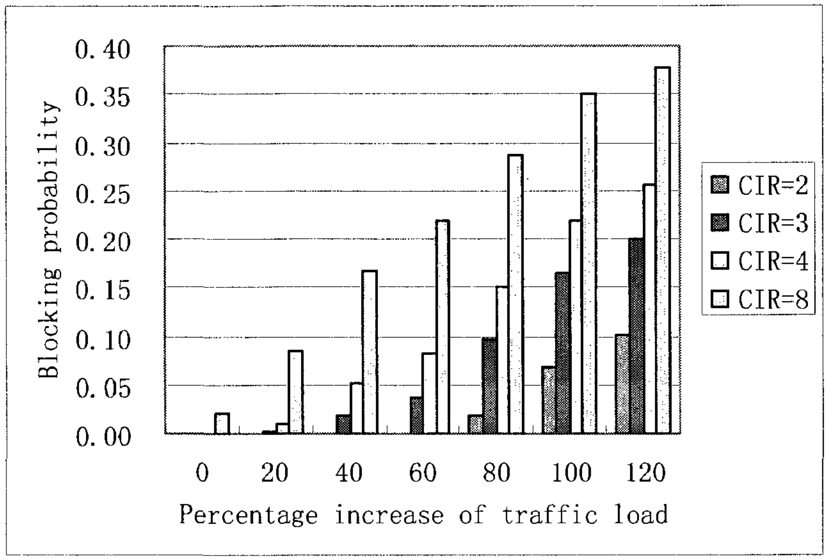

Figure 4.13: Effect of CIR on blocking probability for ratio 21:49 for ILP3

In addition, we study how the blocking probability is affected by using different values of CIR. The higher the value of CIR, the better the QoS for the communication. However, this increase in quality comes at a price. In order to accommodate the higher CIR value, two calls using the same channel must be separated by a larger distance. This results in a lower channel utilization and a corresponding increase in blocking probability, as shown in Figure 4.13.

Finally, we compare ILP3 with ILP4 with same parameters. Figure 4.14 shows the result for ratio 35:35 with CIR=3. From it we can see that their blocking probabilities are very close to each other. The situation remains similar when testing for different FC:DC ratios with different CIR values. We think this is because that, in this scenario, only co-channel interference is taken into consideration. The improvement of reassignment over non-reassignment will become apparent when we consider co-site and adjacent channel interference simultaneously. However, more simulations should be conducted to fully study their properties.

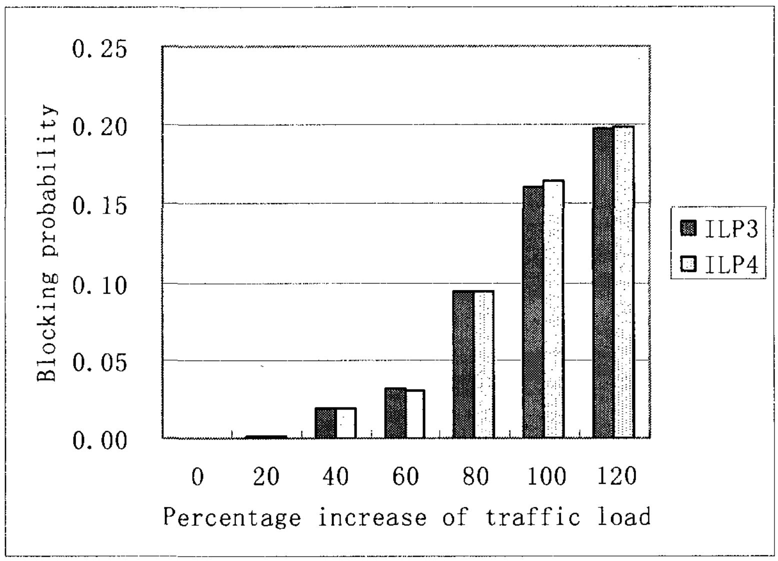

Figure 4.14: Comparison between ILP3 and ILP4 for ratio 35:35 with CIR=3

5. Conclusion and Future Work

In this paper we have presented two new sets of integer linear programming formulation for hybrid channel assignment in wireless cellular networks. The first set does not consider power control problem, while the second set of formulation is capable of integrating power control.

For the first series, to the best of our knowledge, this is the first time to optimally solve the hybrid channel assignment problem that takes into consideration the co-site and the adjacent channel constraints, in addition to the co-channel constraints. The results indicate that even without channel reassignment, our approach (with ILP1) produces results comparable to some existing schemes that perform reassignment. Additional improvements can be obtained if we allow channel reassignment (with ILP2) as well.

The second set of ILP formulation is aiming the combined channel assignment with power control. Our approach not only selects an available channel for a new incoming call, but also determines the appropriate transmission power level for all calls using the selected channel. The goal is to select a channel such that the total power consumption for all calls (including the new call) using that channel is minimized, while ensuring that the

CIRs of all existing calls and the new call are maintained above a specified threshold. Therefore, unlike many previous approaches, we guarantee that no ongoing calls will be dropped due to the introduction of the new call. Experimental results show that our approach leads to a significant reduction in blocking probability, compared to techniques both CIR based (without power control) and reuse distance based.

For the future work, we will study the CIR based QoS measurement when applied to co-site and adjacent channel constraints, thereby enhance our ILP formulations.

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