國立臺灣大學資訊管理學研究所博士論文

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無線通訊網路資源分配與管理

Resource Allocation and Management in Wireless Communication Networks

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中華民國九十二年元月

中文摘要

近年來拜行動通訊科技快速發展所賜，行動通訊服務需求量持續升高，各項新穎之行動通訊加值服務與多元化行動通訊功能不斷推廣。有鑑於行動通訊網路系統均具備多種網路資源管理之高度複雜性，為求整體通訊效能之確保以及構建與營運成本之控制，本論文的研究內容包括：(1) 整合式網路規劃 (integrated network planning)、(2) 網路效能優化 (performance assurance & optimization) 以及 (3) 即期性網路效能回復 (network servicing) 三大模組。

整合式網路規劃模組針對行動通訊網路系統，透過數學最佳化方法之推演以決定所採用之無線通訊基地台配置、方向性天線規劃、功率控制、頻道配置與傳輸設備容量配置，其最終目的在滿足網路效能條件限制下，儘量降低系統之構建與營運成本。網路效能優化模組則植基於網路規劃架構、訊務量分佈以及訊務模型特性之考量，最佳化調整網路系統參數與管制系統資源，進而優化系統效能標的。至於即期性網路效能回復模組則是當網路效能劣化時，必須即期考慮當時之基地台資源配置、網路負載以及訊務分佈，藉由路由重設 (rerouting) 及容量擴增 (capacity augmentation) 等策略儘快使劣化之系統效能回復正常。

本論文針對頻道再利用所造成之干擾現象，考量廣用型無線電波傳播特性，發展出一般性頻道干擾數學模型以及彈性頻道分配演算法，在整體考量同頻干擾與鄰頻干擾以確保通訊品質之前提下，達到效能最佳化之目的。並且由於無線通訊仰賴之無線電波傳輸媒介易招受天然氣候與人為環境之干擾，通訊服務之可靠度 (reliability) 乃成為一項無線通訊規劃與管理之重要議題，本論文亦探討多重連線 (multiple-connectivity) 在無線通訊網路整體規劃與資源分配之影響，發展出循序尋徑 (sequential routing) 演算法與相關數學模型。本論文植基於此兩項數學演算法為核心發展出上述三模組之最佳化模型，形成完整之無線通訊網路資源分配與管理研究。

由於此類問題的本質均具高度複雜性與困難度，為求最佳化決策之時效與品質，特採用數學模式化 (mathematical formulation) 以及數學規劃法 (mathematical programming) 等最佳化技巧為基礎方略，特別是利用拉格蘭日鬆弛法 (Lagrangean Relaxation) 在解決複雜度高之最佳化數學問題上有非常好之表現，此種數學最佳化模式所展現在各模組之實驗結果顯示相較於一般性之方法迭可獲致數倍之效能或成本改良。

關鍵字：無線通訊網路、網路規劃、效能最佳化、即期性網路效能回復、循序尋徑、多重連線、頻道分配、網路最佳化、拉格蘭日鬆弛法。

ABSTRACT

GRADUATE INSTITUTE OF INFORMATION MANAGEMENT

NATIONAL TAIWAN UNIVERSITY

NAME: CHIH-HAO LIN MONTH/YEAR: JANUARY/2003

ADVISER: FRANK YEONG-SUNG LIN

Resource Allocation and Management in
Wireless Communication Networks

With the rapid growth of advanced wireless technologies, the mobile applications are considered necessary by most people. Being able to well designed and efficiently manage wireless communication networks is a critical issue for operators to optimize their system revenue. In this dissertation, we identify several research topics and critical issues about wireless communication networks, which consist of three modules: (1) integrated network planning, (2) performance assurance and optimization and (3) network-servicing modules.

In the integrated network planning module, we deal with reliable network design problem by considering base station allocation, sectorization, power control, channel assignment, homing policy, multiple-connectivity and capacity management problems altogether. The objective is to minimize total network installation cost subject to several quality of service, grade of service, configuration and performance constraints. In the performance assurance and optimization module, we try to optimize system performance by considering the existing system architecture, traffic distribution, traffic load and quality of service requirements. The objective is to minimize the total loss revenue in the system by adopting admission control, channel assignment and homing policies. In the network-servicing module, due to traffic growth and traffic distribution change, system becomes infeasible and inefficient. To adopt

channel re-assignment, power control, re-homing and channel augmentation policies to facilitate the network is the major objective of this module.

The emphases of this dissertation are to develop a generic channel interference model and a sequential routing model for channelized wireless communication networks. To ensure communication quality of service, we propose a generic channel interference model for the flexible channel assignment problem considering co-channel, adjacent channel and near channel interferences. Owing to the unstable properties of wireless air interface, we apply a sequential routing algorithm to guide realtime homing sequence under reliable multiple-connectivity wireless networks. Furthermore, these two algorithms can help to develop the integrated network planning, performance optimization and network servicing modules.

To fulfill the timing and the quality of the optimal decisions, we construct several mathematical formulations that can further enhance performance and reduce cost than general methods. Lagrangean relaxation method, having been proved good in solving the complicated mathematical mode, is chosen to solve our problems.

Keywords: Wireless Communication Networks, Network Planning, Performance Optimization, Network Servicing, Sequential Routing, Multiple Connectivity, Channel Assignment, Network Optimization and Lagrangean Relaxation.

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1. Introduction

1.1 Overview

Technological advances and rapid development of handheld mobile terminals (MTs) have facilitated the rapid growth of wireless communications. Due to the economic factors and the new trend in the telecommunications industry, the population of mobile users will continue to grow at a tremendous rate. The scarcity of spectrum resource necessitates efficient allocation and management mechanisms. Efficient use of radio spectrum is also important from a cost-of-service point of view, where the number of base stations (BSs) is required to service a given geographical area. In order to efficiently utilize the spectrum resource, frequency resource management is becoming one of the most important issues for channelized wireless networks. Since higher resource utilization can achieve higher revenues, how to assign channel resources and how to organize cell configuration to optimize resource utilization have become critical issues in wireless networks.

To identify research issues systematically, we analyze the research scope composed of three modules: network planning, performance assurance/optimization and network servicing modules. When we consider wireless communication networks, the first problem is the network-planning problem. That is, we want to deploy a feasible and efficient wireless network to serve all potential mobile users in the system. We must satisfy several constraints, consisting of configuration, capacity, connectivity, receiver sensitivity, carrier-to-interference ratio (CIR) and quality of service (QoS) constraints. The objective function will be to minimize the total installation cost of wireless systems, such as costs of (1) fixed installation cost of BSs, (2) capacity equipment cost and (3) the spectrum-licensing fee. This problem is one kind of resource allocation issues.

After the wireless system has been deployed, the operators must well manage and maintain the scarce spectrum resource for an in-service communication network. Performance optimization module manages radio resources to ensure communication QoS and optimize system performance. For a channelized wireless system, the major issues of performance optimization are admission control, channel assignment and homing. The major objective of performance assurance/optimization is to optimize long-term average system revenue by using admission control, channel assignment and homing policies.

Due to traffic growth and traffic distribution change, the performance exceptions will occur on an in-service network. Network servicing module is used to alleviate performance exceptions by using corrective mechanisms, consisting of resource augmentation, channel reassignment, transmission power rearrangement and rehoming issues. Channel reassignment may be required in a wireless communication network when channel interference and/or the distribution of traffic demand changes. Like channel reassignment, sector transmission power control and rehoming are effective and economical measures to alleviate performance problems. However, when the traffic demand exceeds a critical point and the current network capacity becomes insufficient, channel augmentation is required despite the application of the above-mentioned three cost-effective measures.

The emphases of this dissertation are to develop a measurement-based interference model and a sequential homing algorithm. Under a generic radio propagation environment, the measurement-based interference model accumulates total interferences to ensure communication QoS. For a multiple-connectivity network, sequential homing algorithm can help to decide realtime homing sequence by optimizing long-term system performance to support reliability wireless communication service.

We formulate these problems as combinatorial optimization problems, which are NP-complete and are composed of integer, non-convexity and non-linear properties. To fulfill the timing and the quality of the optimal decisions, the solution approach to the mathematical problems is Lagrangean relaxation method. In the computational experiments, our proposed algorithms are shown to be efficient and effective to deal with each complexity problems in this dissertation.

1.2 Research Scope

The scope of this dissertation is depicted in Figure 1.1. In this dissertation, we develop two kernel algorithms in wireless communication networks. The first is the flexible channel assignment (FlCA) algorithm and the other is the sequential homing algorithm. By using classification, we analyze systematically the resource allocation and management problems and identify several research topics. We group our main researches into three main optimization modules and discuss in the following.

(1) Integrated network-planning module: to design a reliable wireless network with minimum installation and operation cost. This design problem together considers BS allocation, sectorization, power control, channel assignment, homing policy, multiple-connectivity and capacity management problems. The objective is to minimize total network deployment cost and spectrum license fee subject to several QoS, configuration and performance constraints.

(2) Performance assurance and optimization module: to optimize a certain system performance measure by considering the existing system architecture, traffic distribution, traffic load and QoS requirements for an in-service communication

network. The objective is to minimize the total loss revenue in the system by adopting admission control, channel assignment and routing policies.

(3) Network-servicing module: by using corrective actions to alleviate the performance exceptions due to traffic growth and traffic distribution change. For channelized communication networks, these corrective actions consist of channel re-assignment, power control, re-homing and channel augmentation policies.

In this section, we also identify several critical issues for the resource allocation and performance management problems and depict their relationships with finite-state-machine form in Figure 1.2. In this figure, we use two system states to differentiate realtime and periodic operational objectives. There are nine transitions in the system to perform possible treatments for the corresponding system state. A system staying at State 1 means that a great majority of traffic requirements can be serviced by this system and that all the in-service requirements must satisfy QoS constraints. In this state, three operational treatments can optimize realtime system performances. These treatments consist of admission control, channel assignment and homing policies.

If applying all of these mechanisms to wireless system still violates the call-blocking probability constraints, it means that current system resource becomes insufficient due to the growth of traffic demands or the change of traffic distributions. Transition 4 will be triggered and it will transfer the system state to the scheduled/predictive augmentation state, denoted as State 2. At State 2, system operator can adopt four treatments to rearrange and/or augment system resource to alleviate the performance exceptions. These mechanisms consist of, channel reassignment, rehoming, configuration rearrangement and channel augmentation. After the amendment of network servicing module, wireless networks will transfer to State 1 again. We describe these mechanisms as follows.

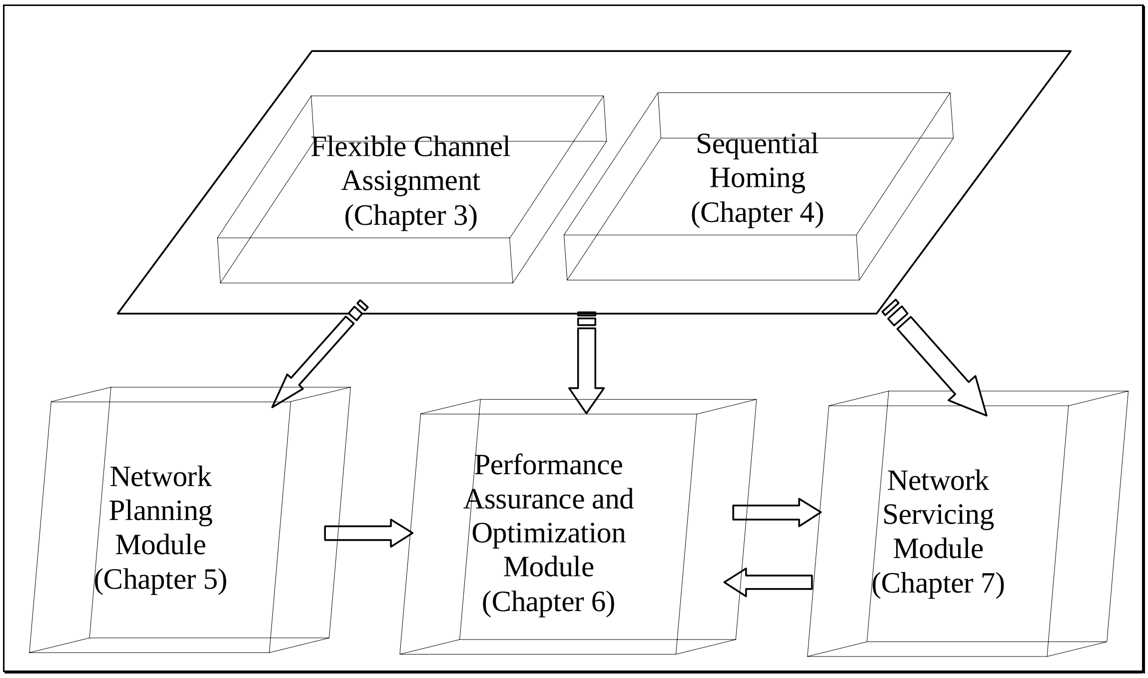

Figure 1.1: Research scope of this dissertation

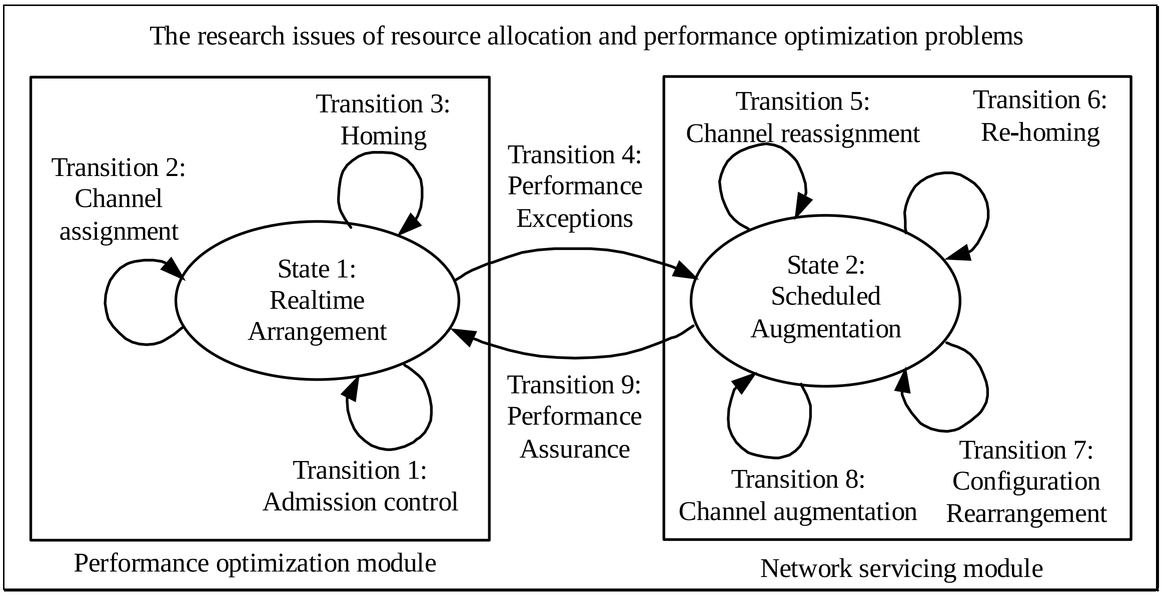

Figure 1.2: The research issues of resource allocation and performance management

- Admission control: Whenever a new traffic demand arrives, admission control mechanism must be applied immediately to decide whether the system can grant this new requirement or not. The new grant decision should satisfy all of the system constraints and cannot violate the QoS requirements of existing users.

- Channel assignment and re-assignment: Considering co-channel interference (CCI), adjacent channel interference (ACI) and configuration constraints, channel assignment mechanism will assign enough feasible channels to each cell to optimize resource utilization. Channel reassignment may be required in a wireless network when channel interference or new channels become available to optimize resource utilization.

- Configuration re-arrangement: If the distribution of traffic demand changes due to populations shift, these mechanisms are indispensable regardless of the fact that channel reassignment may solve some kinds of performance exceptions. Power control changes transmission power level of each antenna. Furthermore, configuration re-arrangement can periodically amend antenna coverage by tuning both sector radian and power level for each antenna.

- Homing and re-homing: For satisfying call-blocking constraint purpose, load balance policy prefers to home a new traffic demand or re-home an existing one to the lower utilization cell in order to minimize the total amount of system required channels.

- Channel augmentation: When the traffic demand exceeds a critical point and the current network capacity becomes insufficient, channel augmentation is required to expand network capacity. The objective of this mechanism is to minimize the long-term channel license fee subject to the call-blocking constraint and coverage constraint.

The emphasis of this dissertation is to combine the measurement-based interference model and the sequential homing algorithm into the mentioned three modules. Due to the unstable properties of wireless air interface, sequential homing algorithm can integrate with the network-planning module in order to design reliable multiple-connectivity wireless networks. Furthermore, this mechanism can also be combined with the performance assurance/optimization module to support realtime homing sequence by optimizing long-term system performance. The measurement-based interference model accumulates both CCI and ACI to ensure communication QoS in a generic radio propagation environment.

1.3 Dissertation Organization

The organization of this dissertation is as follows: In Chapter 2, we provide the backgrounds of this dissertation. We group the literatures into three parts, including (1) frequency resource technologies, (2) wireless resource allocation and management, and (3) mathematical models.

In Chapter 3, we develop an FlCA algorithm to allocate and manage frequency resource more effective by taking the advantages of both fixed channel assignment (FCA) and dynamic channel assignment (DCA) schemes to optimize system performance.

To consider reliability issue in virtual circuit networks, we propose a sequential homing problem in Chapter 4. We formulate a generic sequential homing problem as a sequential routing algorithm considering multiple-connectivity requirement.

In Chapter 5, we consider the network-planning problem in channelized wireless communication networks. We combine the generic measurement-based interference model and the sequential homing algorithm into wireless network design problem to ensure generic communication QoS and customized multiple-connectivity requirements.

In Chapter 6, we consider the performance assurance and optimization module in wireless communication networks. We develop a centralized performance optimization algorithm by combining sequential homing and fixed channel assignment mechanisms on multiple-connectivity networks.

When the wireless networks become insufficient resulting from demand increase or traffic distribution change, we apply the network-servicing module to alleviate the performance exceptions by adopting channel re-assignment, channel augmentation, power control and re-homing mechanisms. We deal with channel re-assignment, power control, rehoming and channel augmentation mechanisms of network-servicing module in Chapter 7

Finally, we conclude this dissertation by summarizing this dissertation and proposing the future research in Chapter 8.

2. Research Background

2.1 Frequency Resource Technologies

The increasing density of cellular mobile communication networks requires the accurate characterization of radio propagation channels for an efficient spectrum management. Because the channel characteristics vary from one environment to another, an effective design, assessment and installation of a radio network requires an accurate characterization of the channel. Having an accurate channel characterization for each frequency enables the designer or user of a wireless system to predict signal coverage and the specific performance attributes of alternative signaling and reception schemes. Channel models are usually used to determine the optimum location for installation of antennas and to analyze the interference between different systems [17].

2.1.1 Radio Propagation Models

Radio propagation in any environment is complicated by the fact that the shortest direct path between transmitter and receiver is usually blocked by buildings, mountains and terrain features outdoors. The received signal is typically carried from the transmitter to the receiver by multiplicity paths with various strengths. The deterministic analysis of propagation mechanisms in such an environment is limited to simpler cases. Statistical analysis is more useful and indeed more typically used for complex cases. We summarize the notation definitions in Table 2.1.

Table 2.1: Notation descriptions

Parameters	
Notation	**Description**
ε_m	average antenna height of all mobiles above local terrain height [m], often taken as 1.5m
ε_b	BS antenna height above local terrain height [m]
ε_o	mean height of a building above local terrain height [m]
d_m	distance between the mobile and the nearest building [m]
η_c	carrier frequency [MHz]
κ	free space wavelength [m]
r	great circle distance between BS and mobile [km]
σ_s	the angle between the street and the direct line from base to mobile
ϕ_r	the reflection loss (=0.25)
ϖ	the average longer paths between the buildings for oblique incidence
ϖ_m	the distance between the building faces on either side of the street containing the mobile (typically $w_m = w/2$)
σ_e	the elevation angle of the BS antenna from the top of the final building [radians]

2.1.1.1 The Empirical Models

The important parameter for the Macrocell designer is the overall area covered, rather than the specific field strength at particular locations. The basic definition of a Macrocell is that $\varepsilon_b > \varepsilon_o$. Typical BS heights in practice are around 15 m if a mast is used, or around 20 m upwards if deployed on a building rooftop. The effective BS height may be increased dramatically by locating it on a hill overlooking the region to be covered [77]. The most widely quoted macro-cell model is the Okumura-Hata model [29]. This model is a fully empirical prediction method, based entirely upon an extensive series of measurements made in and around Tokyo city between 200 MHz and 2 GHz by Okumura in 1968. The Okumura-Hata model involves dividing the prediction area into open, suburban and urban areas. Hata's approximations are described as follows [29]:

Urban areas: $\phi_{dB} = A + B\log r - E$

Suburban areas: $\phi_{dB} = A + B\log r - C$

Open areas: $\phi_{dB} = A + B\log r - D$

where

$$A = 69.55 + 26.16\log f_c - 13.82\log h_b$$

$$B = 44.9 - 6.55\log \varepsilon_b$$

$$C = 2(\log(\eta_c / 28))^2 + 5.4$$

$$D = 4.78(\log \eta_c)^2 + 18.33\log \eta_c + 40.94$$

$$E = 3.2(\log(11.75\varepsilon_m))^2 - 4.97 \qquad \text{(for large cities, } \eta_c \geq 300MHz\text{)}$$

$$E = 8.29(\log(1.54\varepsilon_m))^2 - 1.1 \qquad \text{(for large cities, } \eta_c < 300MHz\text{)}$$

$$E = (1.1\log \eta_c - 0.7)\varepsilon_m - (1.56\log \eta_c - 0.8) \qquad \text{(for medium to small cities).}$$

This empirical propagation model is valid only for frequencies in the range of 150 MHz to 1500 MHz, $30\,\text{m} \leq \varepsilon_b \leq 200\,\text{m}$, $1\,\text{m} \leq \varepsilon_m \leq 10\,\text{m}$ and $r > 1\,\text{km}$. The path loss exponent is given by *B*/10, which is a little less than 4, decreasing with increasing BS antenna height.

The Okumura-Hata model for medium to small cities has been extended to cover the band 1500 MHz < η_c < 2 GHz [12].

$$\phi_{dB} = F + B\log r - E + G$$

where

$$F = 46.3 + 33.9\log \eta_c - 13.82\log \varepsilon_b$$

$$E = (1.1\log \eta_c - 0.7)\varepsilon_m - (1.56\log \eta_c - 0.8)$$

$$G = \begin{cases} 0\,\text{dB} & \text{medium-sized cities and suburban areas} \\ 3\,\text{dB} & \text{metropolitan areas} \end{cases}$$

2.1.1.2 The Physical Models

Although empirical models have been extensively applied with good results, they suffer from a number of disadvantages [77]:

(i) Only be used over parameter ranges included in the original measurement set.

(ii) Environments must be classified subjectively according to categories.

(iii) No physical insight into the mechanisms such as an unusually large building or hill in particular locations.

That is, when a macrocell system is operated in a built-up area with reasonably flat terrain, the dominant mode of propagation is multiple diffractions over the building rooftops. The Ikegami model attempts to produce an entirely deterministic prediction of field strengths at specified points [32]. Using a detailed map of building heights, shapes and positions, ray paths between the transmitter and receiver are traced, with the restriction that only single reflections from walls are accounted for. Diffraction is calculated using a single edge approximation at the building nearest the mobile and wall reflection loss is assumed to a constant value [77].

$$\phi_E = 10\log\eta_c + 10\log(\sin\sigma_s) + 20\log(\varepsilon_o - \varepsilon_m) - 10\log\varpi - 10\log\left(1 + \frac{3}{\phi_r^2}\right) - 5.8$$

The model assumes that the elevation angle of the BS from the top of the knife-edge is negligible in comparison to the diffraction angle down to the mobile level. The analysis assumes that the mobile is in the center of the street. The predictions suggest that field strength is broadly independent of a mobile’s position across the street. The disadvantage of this model is that it assumes BS antenna height does not affect propagation. That makes the model inclined to underestimate loss at large distances compared with measurements [77].

The full multiple edge integral must take very long computation times to predict the BS coverage over a wide area, which would require a large number of individual path profiles. For the purpose of simplification, the Walfisch-Bertoni model is one limiting case of the flat edge model, which assumes all of the building to be equal height and spacing [89]. The model assumes that the number of buildings is sufficient for the field to settle. The Walfisch-Bertoni model was the first to actually demonstrate that multiple building diffraction accounts for the variation of distance with range which is observed in measurements [89].

$$\phi_{ex} = 57.1 + \log \eta_c + 18 \log r - 18 \log(\varepsilon_b - \varepsilon_o) - 18 \log\left[1 - \frac{r^2}{17(\varepsilon_b - \varepsilon_o)}\right]$$

$$+ 5 \log\left[\left(\frac{\varpi}{2}\right)^2 + (\varepsilon_o - \varepsilon_m)^2\right] - 9 \log \varpi + 20 \log\left\{\tan^{-1}\left[\frac{2(\varepsilon_o - \varepsilon_m)}{\varpi}\right]\right\}$$

The use of the settled field approximation requires that large numbers of buildings are present, particularly when σ_e is small.

The Walfisch-Bertoni model for the settled field has been combined with the Ikegami model for diffraction down to street level and some empirical correction factors to improve agreement with measurements in a single integrated model by the COST231 project. For non-line-of-sight conditions the total loss is given by [12]:

$$\phi = \phi_F + \phi_{msd} + \phi_{sd}$$

where

$$\phi_F = 32.4 + 20 \log r + 20 \log \eta_c$$

$$\phi_{sd} = -16.9 + 10 \log \eta_c + 10 \log \frac{(\varepsilon_b - \varepsilon_o)^2}{\varpi_m} + \phi(\sigma_s)$$

$$\phi_{msd} = \phi_{bsh} + u_a + u_d \log r + u_f \log \eta_c - 9 \log \varpi$$

$$\phi(\phi) = \begin{cases} -10 + 0.354\sigma_s & \text{for } 0^{\circ} < \sigma_s < 35^{\circ} \\ 2.5 + 0.075(\sigma_s - 35^{\circ}) & \text{for } 35^{\circ} < \sigma_s < 55^{\circ} \\ 4.0 - 0.114(\sigma_s - 55^{\circ}) & \text{for } 55^{\circ} < \sigma_s < 90^{\circ} \end{cases}$$

$$\phi_{bsh} = \begin{cases} -18 \log[1 + (\varepsilon_b - \varepsilon_o)] & \text{for } \varepsilon_b > \varepsilon_o \\ 0 & \text{for } \varepsilon_b \le \varepsilon_o \end{cases}$$

$$u_a = \begin{cases} 54 & \text{for } \varepsilon_b > \varepsilon_o \\ 54 - 0.8(\varepsilon_b - \varepsilon_o) & \text{for } r \geq 0.5 \text{ km and } \varepsilon_b \leq \varepsilon_o \\ 54 - 0.8\dfrac{(\varepsilon_b - \varepsilon_o)r}{0.5} & \text{for } r < 0.5 \text{ km and } \varepsilon_b \leq \varepsilon_o \end{cases}$$

$$u_d = \begin{cases} 18 & \text{for } \varepsilon_b > \varepsilon_o \\ 18 - 15\dfrac{(\varepsilon_b - \varepsilon_o)}{\varepsilon_o} & \text{for } \varepsilon_b \leq \varepsilon_o \end{cases}$$

$$u_f = \begin{cases} -4 + 0.7\left(\dfrac{\eta_c}{925} - 1\right) & \text{for medium - sized city and suburban areas} \\ -4 + 1.5\left(\dfrac{\eta_c}{925} - 1\right) & \text{for metropolitan centres} \end{cases}$$

where ϕ_F is the free space loss, ϕ_{ms} accounts for multiple knife-edge diffraction to the top of the final building and ϕ_{sd} accounts for the single diffraction and scattering process down to street level. The model is applicable for 800 MHz$\leq \eta_c \leq$2000 MHz, 4 m$\leq \varepsilon_b \leq$50 m, 1 m$\leq \varepsilon_m \leq$3 m and 0.02 km$\leq r \leq$5 km.

2.1.1.3 The Proposed Extended COST231 Model

The propagation environment is characterized by digital terrain databases. These databases generally contain both height information and land-cover data; the former is stored in a topographical database while the latter is collected in a land-usage database. In some publications, the term “morphography” is used instead of “land usage [46].”

Scattering, diffraction and attenuation of radio propagation in the receiver near range (RNR) may cause significant additional path loss [45]. Near-range models apply for the corresponding areas in forest and urban sites. Wave-propagation models for rural areas consider mainly the influence of topography. In this model, we consider the effects from both topography and morphography. That is, the main propagation paths are over rural areas, influenced by the large-scale topography, whereas propagation near the receiver is determined by the near-range land usage [47].

The usual approach to calculation about obstruction loss is to represent peaks in the terrain by a series of equivalent absorbing knife-edges [46]. This makes the implicit assumptions that (1) the terrain peak is sharp enough to be represented by a knife-edge and (2) the peak is wide enough transverse to the path to neglect any propagation from around the sides of the hill.

$$\phi_{ke}(\nu) \approx -20\log\frac{1}{\pi\nu\sqrt{2}} \approx -20\log\frac{0.225}{\nu}$$

where

$$\nu = h'\sqrt{\frac{2(d_1'+d_2')}{\lambda d_1' d_2'}} = \alpha\sqrt{\frac{2d_1' d_2'}{\lambda(d_1'+d_2')}}$$

Notation h' is the excess height of the edge above the straight line from source to field points. For most practical cases, $d_1, d_2 >> h$, so the diffraction parameter ν can be approximated in terms of the distances measured along the ground:

$$\nu \approx h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = \alpha\sqrt{\frac{2d_1 d_2}{\lambda(d_1+d_2)}}$$

If there are several edges, the more accurate approximate multiple knife-edge diffraction model can be applied. The Deygout method is simple to apply and can give reasonable results under restrictive circumstances [13]. The total excess loss is calculated by combining the loss from the main edge and from each of the two sub-paths. And then, this excess obstruction loss must be combined with the free space loss to give the total loss.

Two-dimensional wave propagation models (wave propagation is only regarded in a vertical transmitter and receiver propagation plane) represent the influence of topographical obstacles by single knife-edge model. The influence of land usage is regarded by COST231 model. We suggest that using the extend COST231 model as our propagation model to consider both topographical and morphographical obstruction losses by: $L = L_F + L_{ke} + L_{msd} + L_{sd}$.

2.1.2 Frequency Spacing

The global system for mobile communication (GSM) recommendations stated that reference interference will be achieved at a CIR margin of 9 dB for CCI and that the margin is –9 dB for ACI. Channel impairments such as crosstalk, premature handoffs and dropped calls may result from ACI, leading to degradation of QoS. Although channel filters in both the BS and the MT significantly attenuate signal from adjacent channels, severe interference may occur in circumstances where the received signal level of an adjacent channel greatly exceeds that of the desired channel [38].

To reduce ACI, typical cellular systems employing channel assignment schemes avoid the use of adjacent channels in the same BS. That is, channels immediately adjacent to each other in frequency are assigned to different cells and the distance plays a key role in reducing their mutual interference. In channelized radio system, the ACI is suppressed by the filter and by a distance factor. A common approach to optimize the spectrum efficiency has been to pick an appropriate frequency reuse distance in order to keep the CCI constrained. The ACI has been suppressed by selecting a rather large channel separation. However, this approach is not likely to achieve the optimum spectrum efficiency because the designer must account for ACI and CCI simultaneously.

To maintain the quality of the links and achieve percentiles type of coverage requirements, the CIR must exceed the receiver’s minimum requirements for acceptable transmission in at least 95% of the cell areas. If the power from each BS is known and given a specific channel assignment and separation policies, the probability density function for the CIR can be computed. The channel reuse policy influences the magnitude of both CCI and ACI, while the ACI only affects the channel separation [26].

Several researchers have studied the frequency spacing problem in order to allow the maximum number of channels in a given bandwidth [63]. The fact that the ACI is small provides an opportunity to reduce the frequency spacing between adjacent channels, which would significantly increase the spectral utilization efficiency. The objective is to optimize spectrum efficiency by maximizing total number of channels on the available bandwidth subject to satisfy an acceptable performance requirement.

The ratio between received ACI and CCI can be defined as net filter discrimination (NFD), which describes the discrimination of ACI over CCI due to frequency spacing Δf between consecutive carriers and modulation spectrum shape. We denote the total bandwidth of the system as U (Hz), which is divided into $|F|$ (i.e. $|F| = U/\Delta f$) channels. Let's assume that the filter characteristics of transmitter and receiver are matched, the NFD ratio can be formulated as a function of frequency spacing [63].

$$\theta(\Delta f) = \frac{\int_{-\infty}^{\infty} \Psi(\eta)\cdot\Psi(\eta+\Delta f)df}{\int_{-\infty}^{\infty} \Psi^2(\eta)df} \tag{2.1.1}$$

The numerator equals the interfering power from an adjacent channel on frequency spacing Δf and the denominator is equal to the CCI from one interferer. Function $\Psi(\eta)$ denotes the filter characteristic. The CIR at the victim BS receiver is determined by filter terms $\theta(\Delta f)$ and interference propagation terms Θ_i. Let all channels in the systems are identical and carry QPSK digital signals with a bit rate (bit/s). The CIR can be formed as a function of the channel separation Δf normalized to ρ:

$$CIR(\Delta f\rho) = \frac{\text{average signal power}}{\text{average interference power}} = \frac{R}{\sum_{-\infty}^{\infty}\theta(i\times\Delta f\rho)\times\Theta_i} \tag{2.1.2}$$

where R is the frequency response of desired signal. Calculation of the NFD involves the modulation spectrum shape. The NFD-curves represent how much an ACI is attenuated compared to a CCI at the same geographical distance because of the channel separation $\Delta f \times \rho$ [63].

Malm and Maseng modeled the cellular system as an infinite hexagonal grid with uncorrelated lognormal interferers. The interfering power from a BS is considered uncorrelated with all other interferers and the interested signal, thus all signals are "power-added" at the receiver. Because the probability density function (PDF) for a sum of several lognormal interferers is unknown, they obtain the mean and variance for an approximated Gaussian distribution from the simulation. The Gaussian PDF resulted in a pessimistic value of the channel separation for outage probability.

Spectrum efficiency is a measure to assess how well the total bandwidth is exploited in a cellular system. Malm and Maseng defined a spectrum efficiency formula, which consider cluster-size, modulation method and bit-rate, as follows [63].

$$\text{Spectrum efficiency} = \frac{\log_2(symbol)}{\Delta f \times \rho \times \Gamma}. \tag{2.1.3}$$

The channel separation is normalized to the bit-rate that corresponds to the number of bits per modulation symbol (i.e. $\log_2(symbol)$) and Γ denotes cluster-size.

The standard channel separations for GSM is equal to 200 kHz/271 kbps = 0.74 Hz/bps. The optimum channel separation for GSM is 130 kHz. However, the cell configurations are not of equal size and propagate on flat terrain in a practical system. These results can be exploited in non-integer cluster-sizes.

In paper [63], Malm and Maseng stated, "An example is NMT 450 (Nordic Mobile Telephony) which is an analog system operating in the 450 MHz band. The original specification stated 25 kHz channel separation with 70 dB adjacent channel selectivity. It turned out that NMT 450 was over-designed on ACI suppression and CCI became the limiting factor with low spectrum efficiency as a result. In the successive NMT 900 system, this flaw was corrected by introducing interleaved channel with 12.5 kHz channel spacing. A restriction was that adjacent channels could not be used in adjacent cells, nevertheless interleaved channels increased the spectrum efficiency." That is, network designer must consider both ACI and CCI simultaneously when channel separation is determined.

2.2 Wireless Resource Allocation and Management

2.2.1 Smart Antenna and Sectorization

Extensive research activity into the area of smart-antenna cellular applications started at the beginning of the 1990's. The smart-antenna techniques are one of the few techniques that are currently proposed for new cellular radio network designs, which will be able to dramatically improve system performance [78]. The main advantages expected with smart-antenna techniques are as follows: (1) higher sensitive reception, (2) possibility to implement systems with spatial-division multiple access, (3) interference cancellation in uplink and downlink functions and (4) mitigation effects of multi-path fading [8].

Smart antennas increase system complexity and cost but provides an additional degree of freedom for the radio network control and planning [33]. The smart-antenna receiver structure and algorithms, network control, and planning are the main cellular system components to be considered [8]. The choice of a smart-antenna receiver today is highly dependent on the air interface and its parameters and the algorithm should be compatible and optimized with radio network protocols.

Most current cellular architectures use sectorization techniques. Spatial filtering for interference reduction simultaneously exploits the smart-antenna at the downlinks and it increases capacity [23]. In spatial filtering for interference reduction, the smart-antenna reduces the level of CCI by spatially selective transmission, makes possible more tight channel reuse, and in this way, increases capacity [75]. Two important factors influence the effectiveness of sectorization: one is the number of sectors per cell and the other is the bandwidth of the directional antenna. Intuitively, the more sectors there are in a cell, the less interference in the system. However, too many sectors at a cell can cause excessive handoffs and increase equipment and operational cost. Therefore, BSs in current cellular systems typically have one to five sectors per cell. For example, the wide-beam tri-sector cell in the first generation cellular mobile system employs three 120˚ antennas to cover one cell. A six-sector cellular system using six 60˚ antennas at a cell is also proposed to improve the capacity of GSM [9].

In this dissertation, generic sectorization model allows irregular BS locations, selective radiuses or transmission power of antennas and any kind of sectorization radians. Therefore, this model can specify several kinds of real wireless networks, such as omni-direction antenna, regular sectorization and irregular smart antenna structures. We use continuous integer numbers to label the existing and augmentation frequencies. Using this naming scheme, we can describe the neighboring relationship between adjacent channels and calculate the channel separation. We depict the generic cell configuration and spectrum usage status in Figure 2.1.

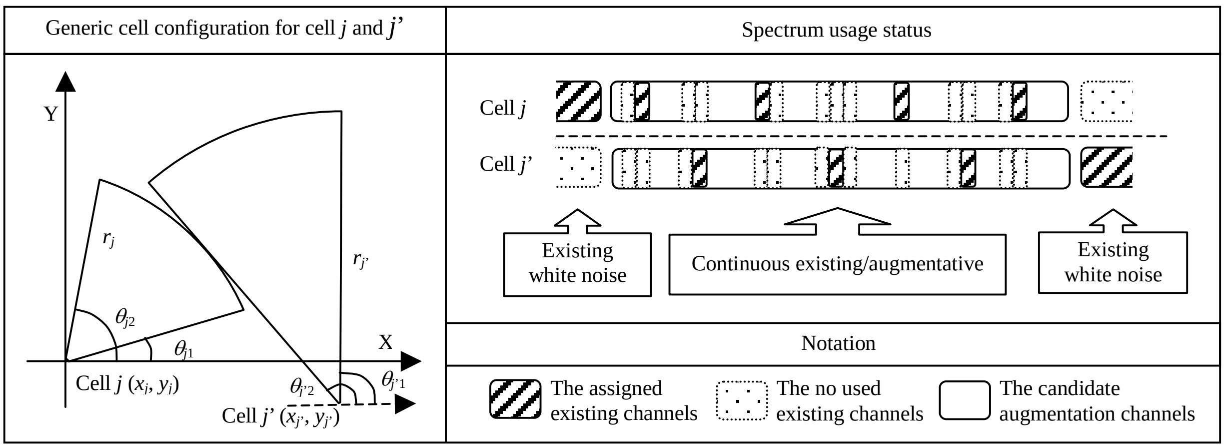

Figure 2.1: Generic cell configuration and spectrum usage status

In our sectorization model, overlapping cells are allowed. That is, some percentage of the MTs may be able to obtain sufficient signal quality from two or more cells. If a call finds its first-attempt home cell has no free channels, it can then try for a free channel in any other cell that can provide sufficient signal quality. We denote this scheme as directed retry. Furthermore, the directed handoff scheme can direct some of the existing calls in its domain to attempt handoff to an adjacent cell when a cell has all or almost all of its channels in use. The motivation is to attempt to redistribute calls in heavily loaded cells to lighter loaded cells. For the directed retry scheme, an increase in the overlapping between cells leads to an increase in the grade of service (GoS) provided by the system. In addition, the directed handoff scheme has very good sensitivity properties with respect to variation in the spatial traffic profile of the system [38].

2.2.2 Channel Assignment

A given radio spectrum can be divided into a set of disjoint or non-interfering radio channels. All such channels can be used simultaneously while maintaining an acceptable received radio signal. In practice, each channel can generate some interference in the adjacent channels. CCI and ACI caused by frequency reuse are the most restraining factors on the overall system capacity in the wireless networks [65]. Channel assignment problems are traditional resource allocation and management problems. The main idea behind channel assignment algorithms is to make use of radio propagation path loss characteristics in order to minimize the CIR and hence increase the radio spectrum reuse efficiency [69].

There are several approaches, such as FCA, DCA and hybrid channel assignment (HCA). The purpose of all channel assignment algorithms is to assign radio channels to wireless users so that a certain level of CIR is maintained at every MT. In FCA schemes, the area is partitioned into a number of cells, and a number of channels are assigned to each cell according to some reuse pattern, depending on the desired signal quality. FCA schemes are very simple, however, they do not adapt to changing traffic conditions and user distribution [38]. In DCA, all channels are placed in a pool and can be assigned to new calls as needed such that the communication QoS is satisfied [44]. At the cost of higher complexity, DCA schemes provide flexibility and traffic adaptability. However, DCA strategies are less efficient than FCA under high load conditions. To overcome this drawback, HCA schemes were designed by combining FCA and DCA schemes [38].

Katzela and Naghshineh define the simple FCA strategy as that the same number of nominal channels is allocated to each cell [38]. Because traffic in cellular systems can be non-uniform with temporal and spatial fluctuations, a uniform allocation of channels to cells may result in poor channel utilization. It is therefore appropriate to tailor the number of channels in a cell to match the load in it by non-uniform channel allocation or static borrowing. In non-uniform channel allocation algorithms, the number of nominal channels allocated to each cell depends on the expected traffic profile in that cell [95]. In the static borrowing scheme proposed in [2], unused channels from lightly loaded cells are reassigned to heavily load ones. This can be done in a scheduled or predictive manner, with changes in traffic known in advance or based on measurements, respectively.

In contrast to FCA, there is no fixed relationship between channels and cells in DCA. All channels are kept in a central pool and are assigned dynamically to radio cells as new calls arrive in the system. After a call is completed, its channel is returned to the central pool [38]. The main idea of all DCA schemes is to evaluate the cost of using each candidate channel and select the one with the minimum cost provided that certain interference constraints are satisfied. The selection of the cost function is what differentiates DCA schemes [38].

In general, there is a trade-off between FCA and DCA. Simulation results show that under low traffic intensity, DCA strategies perform better [37]. However, FCA schemes become superior at high offered traffic, especially in the case of uniform traffic. As shown by simulation in [72], the traffic performance of FCA deteriorates when cells are small, while DCA provides much steadier performance. As discussed in [88], the implementation complexity of the DCA is higher than DCA. Regarding type of control, FCA is suitable for a centralized control system, while DCA is applicable to a decentralized control system [38].

Hybrid channel assignment schemes are a mixture of the FAC and DCA techniques [94]. In HCA, the total number of channels available for service is divided into fixed and dynamic sets. The fixed set of channels are assigned to cells as in the FCA schemes and the dynamic set of channels is shared by all users in the system to increase flexibility as in the DCA schemes. The call blocking probability for an HCA scheme is defined as the probability that a call arriving to a cell finds both the fixed and dynamic channels busy [92]. Katzela and Naghshineh stated, "Simulation results showed that systems with the most dynamic channels give the lowest probability of queuing for load increase up to 15 percent over the basic load. For load increase of 15-32 percent, systems with the medium dynamic channels give the best performance. From load of 32-40 percent, systems with low dynamic channels give the best performance. Finally, for loads of over 40 percent systems with no dynamic channels give the best performance [38]."

In this dissertation, we develop a non-uniform fixed channel assignment scheme in the network-planning problem [53], a directed-retry channel assignment scheme in the performance optimization problem [50], and a flexible channel assignment/augmentation scheme in the resource rearrangement/augmentation problem [49]. In the FlCA schemes, the set of available channels is divided into fixed and flexible sets. Each cell is assigned a set of fixed channels that typically suffices under a light traffic load. The flexible channels are assigned to those cells whose channels have become inadequate under increasing traffic loads. The assignment is done in either a scheduled or predictive manner [83].

2.2.3 Power Control

Antenna power control is one of the most crucial design issues of wireless cellular systems because of its importance in mitigating the CCI and ACI, which stems from frequency reuse in cellular systems [10]. That is, power control schemes play an important role in spectrum and resource allocation in cellular networks. By increasing the transmitted power of the desired signal and/or decreasing the power level of interfering signals, the required CIR level can be accommodated. However, this approach is based on opposing requirements because an increase in the power level of the desired signal level corresponding to a certain MT also results in an increase in the interference power level corresponding to a different MT using the same channel. The purpose of power control scheme is to find a trade-off between the changes of power level in opposing directions [38]. This can result in a dramatic increase of overall system capacity measured in terms of the number of MTs that can be supported [93].

In 1973, Aein investigated CCI management in satellite systems. He introduced the concept of CIR balancing, which yields a “fair” distribution of the interference in the sense that all users experience the same CIR level [93]. The concept was applied and extended to several cellular radio systems and proved substantial improvement on the capacity of such wireless systems [70]. Foschini developed a distributed autonomous power control algorithm that was totally local in that only the power and interference measurements of each BS-MT link is used to evolve power levels on that link [18]. In 2000, Chiang formulated a general power control problem for both CDMA and FDMA systems and transform it into a convex optimization problem with efficient algorithms by using geometric programming [10]. That centralized algorithm can be use to optimize capacity, control QoS and mitigate interference.

In this dissertation, we adopt the power control scheme in both the network-planning and network-servicing modules in generic sectorization networks considering both CCI and ACI.

2.2.4 Network Planning

Cell planning is a very complex task, as many aspects must be taken into account, including the topography, morphology, traffic distribution, existing infrastructure and so on [91]. In 1997, Hao stated [28], “Although many studies have been reported in the areas of mobile cellular network planning in terms of coverage analysis, channel assignment, routing and propagation, relatively few studies have been done regarding the network planning for cost-effective system design." Decisions regarding the number of cells, cell locations, cell configuration, power control, channel assignment and homing schemes should be made within the context of one another [22].

The key element to be considered for cellular network planning is cost. A hierarchical optimization planning approach has been usually used for the production planning of large-scale manufacturing systems and decision making for health care and service systems. Therefore, a three-level optimization approach was presented to determine the radio network architecture, i.e., the number of cells, cell size, cell location, parameters of antenna, antenna height and transmitting power, to serve the area of Singapore [28]. It separately determines the cell number, cell site allocation and the specific BS parameters to minimize the total system cost and to comply with the required system performances. In 1997, Marano developed a Markovian model to design mobile cellular telephony networks considering one cell at a time [64]. In 1999, Bose proposed a dynamic programming scheme to determine the optimal cell geometries and the minimum number of cells required to cover a given area of interest [7]. The author also analyzed the computational complexity of the proposed algorithm and concluded that the computational load grow as $O(|C|^2)$ for fixed values of map resolution and cell coverage in the paper [7]. In 2000, Huang used a fuzzy expert system, a genetic algorithm and a cell splitting technique to develop a three-layered hierarchical model [31].

Because the GSM standard is based on the use of two separate frequency bands, around 900 MHz and 1.8 GHz, respectively. The radius of the 900 MHz cell are larger (up to 35 km) than it of the 1.8 GHz cell (typically less than 1 km) because the much worse propagation characteristics of microwaves in the latter frequency range through the atmosphere. To support design and planning of dual-band GSM networks, Meo proposed approximate analytical models of the system dynamics and exploited the influence of critical system parameters on these analytical models [66].

In this dissertation, we adopt the measurement-based channel interference model to formulate the integrated network-planning problem as a combinatorial optimization problem in Chapter 5. That is, our network-planning algorithm together determines all parameters at once and can be applied on any kind of radio propagation environment [53].

2.3 Mathematical Models

Under the consideration of generic sectorization, propagation and interference effects, we introduce several mathematical formulations to model the associated QoS and GoS requirements in this section [51].

The major communication QoS for channelized wireless systems is downlink CIR constraint [56]. Under the consideration of generic sectorization networks, we propose three kinds of interference estimation models to accumulate interferences from all interfering cells to approximate real interference strength. That is, our models directly consider the CIR at the reception points that take into account interference from multiple sources to more closely model the real problem. Therefore, no explicit channel reuse distance constraints are required.

Although channel filters in both BSs and MTs significantly attenuate signal from adjacent channels, severe interference may occur when the power level of adjacent interfering channels greatly exceeds that of the desired channel. In this dissertation, we together accumulate CCI and ACI in our generic interference model to estimate the total interferences received by MTs [26].

2.3.1 Communication QoS Models

To satisfy the CIR constraints in channelized wireless systems, CCI is usually considered as one of the most important issues. Since ACI may cause channel impairments such as cross-talk effects, premature handoffs and dropped calls, ACI becomes another significant QoS degradation factor in channelized wireless network.

We jointly consider CCI, ACI and near channel interference (NCI) in our generic interference model. We assume that the interfering powers are considered uncorrelated with one another and independent with the desired signal. Therefore, all signals are "power-added" at the receiver. We simply accumulate both CCI and ACI to estimate the total inferences received by MTs. We can formulate the CIR constraint by accumulating all interferences that are received by each MT. For different kinds of applications, we propose three kinds of interference estimation models.

2.3.1.1 BS-based Interference Model

For pure channel assignment or augmentation problems without considering power control or configuration rearrangement, the homing decisions are static. That is, we can construct compatibility matrix for BSs by using BS-based interference model. Each element of compatibility matrix is a function of distance and can be pre-calculated.

In this model, we assume that the MTs may be located anywhere within the boundary of the cell. We can formulate the CIR constraint as

$$\sum_{j'\in A-\{j\}} \sum_{i'\in F} \left(\frac{r_{j'}}{D_{jj'}}\right)^{\alpha} y_{i'j'}\theta(|i-i'|) \le G_j + (\frac{1}{\gamma} + 1 - G_j) y_{ij} \qquad \forall j \in A, i \in F \ .$$

Notation α is the attenuation factor that is usually chosen between 2 and 6 depending on the geography. $D_{jj'}$ is the shortest distance between the interfering BS *j'* and the coverage of interested BS *j*. That is a reference distance for estimating the maximum interference between *j* and *j'*. Notation $r_{j'}$ is the radius of interfering BS *j'*. Function $\theta(\Delta i)$ is the NFD ratio that is a function of the channel separation. Decision variable y_{ij} is channel assignment, which is 1 if Channel *i* is assigned to Sector *j* and 0 otherwise. Threshold of acceptable CIR is

γ. Because Inequality (2.1) will violate whenever $y_{ij} = 0$, we introduce an arbitrarily large number G_j to avoid the violation possibility.

2.3.1.2 Over-estimation Interference Model

When adopting power control or configuration re-arrangement schemes, transmission power of each sector is uncertain before optimizing the system. For QoS assurance purpose, we suggest using the maximum candidate radius of interested sector to substitute uncertain one. Under adopting over-estimation approach, we can assure that any MT homing to interested cell must not violate CIR constraint. We formulate this approach as

$$\sum_{j'\in A}\sum_{i'\in F}\left(\frac{r_{j'}}{D_{jj'}(\bar{r}_j)}\right)^{\alpha} y_{i'j'}\theta(|i-i'|) \le G_j + (\frac{1}{\gamma}+1-G_j)y_{ij} \qquad \forall j \in A, i \in F .$$

Notation $\bar{r}_j$ is the upper bound of transmission radius for Sector *j*. Reference distance $D_{jj'}(\bar{r}_j)$ is the minimum distance between the coverage area of interested Sector *j* with maximum transmission power and the interfering Sector *j'*. That is an over-estimation interferences model of Sector *j*.

2.3.1.3 MT-based Interference Model

In this model, MTs measure the amount of interference to determine the reusability of the channel. A mechanism is assumed to exist by which MTs and BSs can measure the amount of interference. That is, this strength measurement approach estimates the received interferences for each MT by using radio propagation prediction methods or exact power measurement techniques. This exact approach is advantageous on its higher precision at interference power level but disadvantageous on its time complexity that depends on the number of MTs and BSs. In performance optimization module, we can enforce the CIR requirement for MT *t*, which is homed to Sector *j*, by formulating the CIR constraint as

$$k_{tj}\sum_{j'\in A}\sum_{i'\in F}\frac{R_{tj'}}{R_{tj}}y_{i'j'}\theta(|i-i'|)\le G_j+(\frac{1}{\gamma}+1-G_j)y_{ij}\qquad \forall i\in F, j\in A, t\in T.$$

Notations $A/T/F$ denote the sets of sectors/MTs/channels in the system, respectively. Notation k_{tj} is indicator function, which is 1 if mobile *t* can home to Sector *j* and 0 otherwise. The received power of MT t from the downlink signal of Sector *j* is denotes as R_{tj}.

2.3.2 Communication GoS Models

2.3.2.1 Call-Blocking Probability Constraint

For communication networks, call-blocking probability is one of the important QoS for service provider to satisfy customers' requirements. Considering the average performance of resource management, we denote the average traffic of location-based MT *t* as λ_t. The aggregate traffic of Sector *j* is denoted as g_j. The homing decision variable for MT *t* on Sector *j* is denoted as x_{tj}. Its value is set to 1 if MT *t* is homed to Sector *j* and 0 otherwise. We use Erlang-B formula $E(g_j,n_j)$ to denote the call-blocking probability when $g_j=\sum_{t\in T}\lambda_t x_{tj}$ Erlangs of traffic is offered to $n_j=\sum_{i\in F}y_{ij}$ trunks on Sector *j*. The recursion relation of the Erlang-B function is $E(g_j,n_j)=\dfrac{g_j\times E(g_j,n_j-1)}{g_j\times E(g_j,n_j-1)+n_j}$. We can also derive the minimum trunk required function $Q(g_j,\overline{\beta}_j)$ with the condition of call-blocking probability threshold $\overline{\beta}_j$. We can formulate two kinds of call-blocking probability constraints as follows:

$$E(g_j,n_j)\le\overline{\beta}_j\qquad \forall j\in A$$

or $$Q(g_j,\overline{\beta}_j)\le n_j\qquad \forall j\in A$$

where

$$g_j = \sum_{t \in T} \lambda_t x_{tj} \qquad \forall j \in A$$

$$n_j = \sum_{i \in F} y_{ij} \qquad \forall j \in A.$$

2.3.2.2 Call-Dropping Rate Constraint

For existing users, call drop means the communication is interrupted and disconnected. Both frequency hopping and handover mechanisms may cause call drop, which will degrade service quality and lose revenue. We introduce two cost-probability functions Φ_i^F and Φ_t^H. Cost function Φ_i^F is loss of revenue due to channel reassignment on Channel *i*. Cost function Φ_t^H is loss of revenue due to the decision of re-homing MT *t*. The call-dropping constraint can be formulated as

$$\sum_{i \in F} \Phi_i^F \left(y_{ij}(1 - 2z_{ij}) + z_{ij} \right) + \sum_{t \in T} \Phi_t^H \left(x_{tj}(1 - 2h_{tj}) + h_{tj} \right) \le \Phi_j^A \qquad \forall j \in A.$$

Indicator function z_{ij} denotes whether existing Channel *i* is used on Sector *j* or not. Notation h_{tj} denotes the original homing decision. Notation Φ_j^A is the call-dropping loss revenue limitation. Using this formulation, we can describe the reassignment priorities according to channels' usage status and differentiate the reliability priorities of MTs due to different pricing policies.

3. Flexible Channel Assignment Problem

In this chapter, we identify the problem of FlCA in wireless communication networks under the consideration of generic sectorization and channel interference is studied. We formulate this problem as a combinatorial optimization problem, where the objective function is to minimize the average call-blocking rate (or to maximize the total revenue) subject to configuration, QoS, GoS and capacity constraints. The configuration and capacity constraints require that the sectorization policy and assigned capacity for each sector be admissible. The GoS constraint requires that the call-blocking probability be satisfied. The communication QoS enforces the CIR requirement be satisfied. The basic approach to the algorithm development is Lagrangean relaxation. In computational experiments, the proposed algorithm is shown to be efficient and effective. When compared with a number of sensible heuristics, the proposed algorithm achieves up to 99.42% improvement of the total call-blocking rate under an omni-direction channel assignment scenario and 58.15% improvement of the total call-blocking rate under a generic sectorization scenario.

3.1 Introduction

Channel assignment is one of the more important issues for wireless communication researchers. Whether the channel sharing is based upon which multiple access mechanism, there exists a fundamental limit on the number of users sharing the same frequency simultaneously. Since higher resource utilization achieves higher service revenue gains, to optimize system resource utilization becomes the goal of the channel assignment (or allocation) problem [86].

Although various resource management approaches have been proposed to increase the channel efficiency, the majority of current results still focus on hexagonal or regular sectorization network structures due to simplicity of implementation and ease of operation [40]. In this chapter, we consider a more generic channel assignment problem where irregular sectorization policies may be adopted. Generic sectorization structure allows the locations of BSs to be not regular, the radiuses of sectors to be not identical and the radian types of sectorization cells to be not limited. Generic sectorization structure can fit into several kinds of real wireless networks and consider precisely the configurations of real wireless communication systems.

Most of the methods in the literatures follow some “co-channel reuse distance” concepts to assign a channel to interested sector [36]. That is, the same channel being reused some distance away between two sectors. The objective of our algorithm is therefore to develop a mathematical model for arbitrary network structures. We refer to this policy as the QoS assurance approach.

Another interference issue, which is considered by operators of real wireless networks, is ACI effect. Little literatures handle the ACI for channel assignment purpose, but it may influence channel assignment result in real wireless network. MTs homing on the interested sector will receive the ACI from the same sector and others. In this chapter, we together accumulate the CCI and ACI in our QoS assurance approach to calculate the total interferences on MTs.

FlCA problem is a trade off solution between the FCA and DCA problems. It considers not only the FCA problem but also the flexible channel expansion problem. In such a system, given the configuration of existing wireless network and a set of flexible channels, the decision will be how to assign flexible channels to each sector (perhaps daily/hourly based on expected traffic demands of the next day/hour). The model can also be applied to inter-systems/inter-cooperators channel assignment problem. In that environment, those cooperators use neighbor frequencies to service their customer communication demands.

The rest of this chapter is organized as follows. Section 3.2 provides the problem description and mathematical formulation. In Section 3.3, we adopt Lagrangean relaxation as our solution approach. Section 3.4 is our computational experiments. Finally, we conclude this problem in Section 3.5.

3.2 Problem Description

Given the wireless communication system architecture, we formulate the problem as an integer-programming problem where the objective function is to minimize the long-term average call-blocking rate (loss of revenue) of total system subject to several constraints, such as call-blocking probability constraints, configuration constraints of each sector and QoS constraints. Before describing this problem, we define the notations in Table 3.1 and 3.2.

Table 3.1: Notation descriptions for given parameters

Given parameters	
Notation	**Description**
A	the set of sectors
$D_{jj'}$	minimum distance between interested Sector *j* and interfering Sector *j*' under the condition of the transmission radius r_j of Sector *j*
$E(n_j, g_j)$	call-blocking probability function (it is depend on aggregate traffic demand and total assigned channels.)
F'	the set of available flexible channels

G_j	an arbitrarily large number for Sector *j*
N	total number of available channels
g_j	aggregate flow on Sector *j*. (in Erlang)
n_j	the number of original channels which are assigned to Sector *j*
$\bar{n}_j$	upper bound on number of channels that can be assigned to Sector *j*
r_j	transmission radius of Sector *j*
y_{0j}	indicator function is 1 if the existing channel, which is adjacent to channel 1, is originally assigned and 0 otherwise
$y_{(N+1)j}$	indicator function is 1 if the existing channel, which is adjacent to channel |*F*|, is originally assigned and 0 otherwise
α_j	attenuation factor (2< α_j <6) for Sector *j*
β_j	threshold of acceptable call-blocking probability of Sector *j*
γ_j	threshold of acceptable CIR (in dB) of Sector *j*
θ	NFD ratio which is formed as a function of the channel separation (kHz) normalized to the bit-rate (bps)

Table 3.2: Notation description for decision variable

Decision Variable	
Notation	**Description**
y_{ij}	decision variable which is set to 1 if flexible channel *i* is assigned to sector *j* and 0 otherwise

The flexible channel assignment problem for sectorization wireless communication networks can be formulated as the following integer programming problem [48].

Objective function (IP3.1):

$$Z_{IP1} = \min \sum_{j \in A} g_j E(g_j, n_j + \sum_{i \in F'} y_{ij}) \tag{IP3.1}$$

subject to:

$$E(g_j, n_j + \sum_{i \in F'} y_{ij}) \le \beta_j \qquad \forall j \in A \tag{3.1}$$

$$n_j + \sum_{i \in F'} y_{ij} \le \bar{n}_j \qquad \forall j \in A \tag{3.2}$$

$$\sum_{j' \in A} \theta \times \left(\frac{r_{j'}}{D_{jj'}} \right)^{\alpha_{j'}} \left(y_{(i-1),j'} + y_{(i+1),j'} \right) + \sum_{j' \in A - \{j\}} \left(\frac{r_{j'}}{D_{jj'}} \right)^{\alpha_{j'}} y_{ij'} \le G_j + (\frac{1}{\gamma_j} - G_j) y_{ij}$$

$$\forall j \in A, i \in F' \tag{3.3}$$

$$y_{ij} = 0 \text{ or } 1 \qquad \forall j \in A, i \in F' \tag{3.4}$$

$$y_{0j} = 0 \text{ or } 1 \qquad \forall j \in A \tag{3.5}$$

$$y_{(N+1)j} = 0 \text{ or } 1 \qquad \forall j \in A. \tag{3.6}$$

The objective function is to minimize the call-blocking rate of total system. That is, we try to minimize the total loss of revenue in order to maximize system revenue. Constraint (3.1) is to ensure that the blocking probability of each sector is lower than the acceptable call-blocking probability. Constraint (3.2) is to ensure that the number of channels assigned to each sector is under its configuration limitation. Constraint (3.3) is to ensure that the sum of interferences introduced by other co-channel sectors and near-channel sectors is less than the CIR threshold for each flexible channel. The existing channels that are adjacent to flexible channel are denoted by y_{0j} and $y_{(N+1),j}$. Constraint (3.4) is to enforce the integer property of the decision variables. Constraints (3.5) and (3.6) enforce the integer property of the indicator variables.

3.3 Solution Procedure

Because the channel assignment problem is NP-complete [27], we do not expect to develop an efficient optimal algorithm for large-scale problems. Instead, an efficient heuristic algorithm is developed and presented in the following sections. The following lemma specifies the deduction of NP-complete property.

Lemma 3.1: this kind of flexible channel assignment problems is NP-complete

Proof:

By adopting problem reduction technique of NP-completeness, the flexible channel assignment problem (IP3.1) can be reduced as a generalized graph-coloring problem by restricting within regular cellular structures. As we know that a generalized graph-coloring problem is proved a NP-complete problem [27], the problem (IP3.1) is one kind of generalized graph-coloring problems. That is, the kind of network-planning problems is NP-complete.□

3.3.1 Lagrangean Relaxation Method

In applying the Lagrangean relaxation approach, a number of complicating constraints of integer programming problem (IP3.1) are identified. They are then multiplied by Lagrangean multipliers and added to the objective function. This process is referred to as dualizing the complicating constraint. We dualize Constraint (3.3) and construct the following Lagrangean relaxation problem (LR3.1).

Objective function:

$$Z_{LR1}(\mu_{ij}) = \min \sum_{j \in A} g_j E\left(g_j, n_j + \sum_{i \in F'} y_{ij} \right)$$

$$+ \sum_{j \in A} \sum_{i \in F'} \mu_{ij} \left(\sum_{j' \in A} \theta \times \left(\frac{r_{j'}}{D_{jj'}} \right)^{\alpha_{j'}} \left(y_{(i-1)j'} + y_{(i+1)j'} \right) + \sum_{j' \in A - \{j\}} \left(\frac{r_{j'}}{D_{jj'}} \right)^{\alpha_{j'}} y_{ij'} - G_j - \left(\frac{1}{\gamma_j} - G_j\right) y_{ij} \right)$$

(LR3.1)

subject to:

$$E(g_j, n_j + \sum_{i\in F'} y_{ij}) \le \beta_j \qquad \forall j \in A \qquad (3.1)$$

$$n_j + \sum_{i\in F'} y_{ij} \le \bar{n}_j \qquad \forall j \in A \qquad (3.2)$$

$$y_{ij} = 0 \text{ or } 1 \qquad \forall j \in A, i \in F' \qquad (3.4)$$

$$y_{0j} = 0 \text{ or } 1 \qquad \forall j \in A \qquad (3.5)$$

$$y_{(N+1)j} = 0 \text{ or } 1 \qquad \forall j \in A. \qquad (3.6)$$

We can decompose this Lagrangean relaxation problem into $|A|$ independent subproblems.

$$Z_{SUBa} = \min \sum_{j'\in C} \left(\frac{r_j}{D_{jj'}}\right)^{\alpha_{j'}} \theta\left(\mu_{1j} y_{0j'} + \mu_{Nj} y_{(N+1)j'}\right) - \sum_{i\in F'} \mu_{ij} G_j + g_j E(g_j, n_j + \sum_{i\in F'} y_{ij})$$

$$+ \sum_{i\in F'} y_{ij} \left(\mu_{ij} (G_j - \frac{1}{\gamma_j}) + \sum_{j'\in A} \left(\frac{r_j}{D_{j'j}}\right)^{\alpha_j} \theta(\mu_{(i-1)j'} + \mu_{(i+1)j'}) + \sum_{j'\in A-\{j\}} \mu_{ij'} \left(\frac{r_j}{D_{j'j}}\right)^{\alpha_j} \right) \text{(SUB3.1}a\text{)}$$

subject to: (3.1), (3.2), (3.4), (3.5) and (3.6).

3.3.2 The Dual Problem and the Subgradient Method

According to the weak Lagrangean duality theorem, for any $\mu_{ij} \ge 0$, $Z_{LR1}(\mu_{ij})$ is a lower bound on Z_{IP} [15]. The following dual problem (D3.1) is then constructed to calculate the tightest lower bound.

$$Z_D = \max_{\mu_{ih}\ge 0} Z_{LR1}(\mu_{ij}). \qquad \text{(D3.1)}$$

There are several methods to solve the dual problem (D3.1) [14][87], among which the subgradient method is the most popular and is employed here [25][30]. Computational performance and theoretical convergence properties of the subgradient method are discussed in Held, Wolfe and Crowder [25] and on non-differentiable optimization [30]. In this dual problem, let a vector χ be a subgradient of problem $Z_{LR1}(\mu_{ij})$. In iteration k of the subgradient optimization procedure, the multiplier vector π is updated by π^{k+1} =

$\pi^k + \xi^k \chi^k$. The step size ξ^k is determined by $\xi^k = \varsigma \dfrac{Z_{IP1}^h - Z_{D1}(\pi_k)}{\left\|\chi^k\right\|^2}$, where Z_{IP}^h is the primal objective function value for a heuristic. It is an upper bound on Z_{IP1} [60].

3.3.3 Getting Primal Feasible Solutions

When we use Lagrangean relaxation method as our solution approach to these problems, we get not only a theoretical lower bound of primal feasible solutions, but also some hints in the process of solving dual problem iteratively. If the decision variables calculated satisfy the constraints in the primal problem, then a primal feasible solution is found. Otherwise, modification on such infeasible primal solutions can be made to obtain primal feasible solutions. To get primal feasible solutions, we propose the following primal algorithm, denoted by Algorithm *A*.

The overall primal algorithm is described as follows.

- **Algorithm *A*:**

Step 1. (Initialize) For Sector *j* and Channel *i*, we pre-calculate the coefficient

$$\text{Coef}(y_{ij}) = \mu_{ij}(G_j - \frac{1}{\gamma_j}) + \sum_{j' \in A} \left(\frac{r_j}{D_{j'j}} \right)^{\alpha_j} \theta(\mu_{(i-1)j'} + \mu_{(i+1)j'}) + \sum_{j' \in A - \{j\}} \mu_{ij'} \left(\frac{r_j}{D_{j'j}} \right)^{\alpha_j}.$$

Step 2. For Sector *j*, sort the channel coefficients calculated in Step 2 in ascending order, which is referred to as channel order for each sector.

Step 3. Set the iteration counter *k* as the number of flexible channels. At each iteration, we add at most one channel to each sector. Initialize iteration counter *k*=0 and sector counter *c*=0. The total iteration will be the maximum number of available flexible channels, i.e. $0 \le k \le N$. Reset all of y_{ij} to zero.

Step 4. For each sector, calculate the blocking rate reduction $g_j\left(E(g_j, n_j + \sum_{i \in F'} y_{ij}) - E(g_j, n_j + \sum_{i \in F'} y_{ij} + 1)\right)$ if we assign a new channel i to Sector j. Then arrange these values in descending order, which is referred to as sector order.

Step 5. According to the sector order decided in step 4, we choose the cth sector (denoted by j) of sector order.

Step 6. For Sector j, the flexible channel will be the kth channel of the Sector j's channel order. We denote this kth channel for Sector j by i. To decide whether this channel i can be assigned to Sector j or not, we must check the following three constraints.

Step 7. Check the capacity constraint (3.2) for Sector j. If Sector j cannot assign any more channels, go to Step 5.

Step 8. Check the QoS constraint (3.3) for Sector j and channel i. If channel i cannot satisfy the CCI and ACI constraints, go to Step 5.

Step 9. Assign channel i to Sector j by set $y_{ij} = 1$.

Step 10. Increase sector counter by $c=c+1$ until $c \geq |C|$. Then go to Step 5.

Step 11. Increase iteration counter by k++ until $k \geq |F|$. And then go to Step 4.

Step 12. For each sector, check the blocking constraint (3.1). If any violation occurs, use drop-and-add approach to re-assign channels.

3.4 Computational Experiments

3.4.1 Benchmark Problems

We apply our algorithm to many quite different examples discussed in literatures related to the channel assignment problems. We present the results for the application to a 21-cell network. This special example has been considered by many authors working in the field of channel assignment [35][84]. That is, these examples make them possible to compare the derived solutions with previously published results.

The layout of the 21-cell test network is depicted in Figure 3.1. Regarding this network, some different scenarios have been derived by assuming the two different demand vectors D_1 and D_2 shown in Table 3.3. Different values of the so-called co-site constraint (CSC) are assumed in the investigated benchmark problems. This value corresponds to the minimum distance between two frequencies used in the same cell [4]. A value of two in adjacent channel constraint (ACC) implies that adjacent cells cannot use the neighbored frequencies used simultaneously [4].

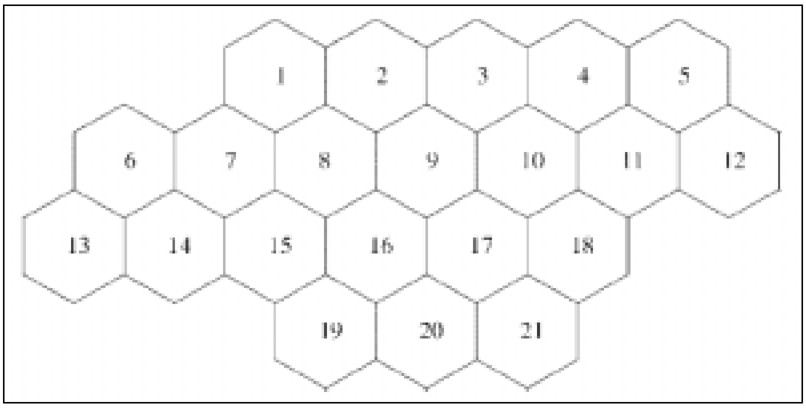

Figure 3.1: The 21-cell test system

Table 3.3: Two channel demand vectors D_1 and D_2

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21
D_1	8	25	8	8	8	15	18	52	77	28	13	15	31	15	36	57	28	8	10	13	8
D_2	5	5	5	8	12	25	30	25	30	40	40	45	20	30	25	15	15	30	20	20	25

Table 3.4 shows the number of required channels which are need by different algorithm in order to derive a valid channel assignment for the problems described by demand vector and interference matrix in the 21-cell system [19].

The comparison of the lower bounds and the frequency demand required by our FlCA algorithm reveals that we are able to find the optimum solutions for all six variants of the given channel assignment problem. We depict the computational results of these six problems in Table 3.5. The *UB* is the total call-blocking rate of our feasible solutions and the *LB* is the lower bound of these problems.

Table 3.4: Channel demands for the 21-cell system

Case	1	2	3	4	5	6
ACC	1	1	2	1	1	2
CSC	5	7	7	5	7	7
Scenario	D_1	D_1	D_1	D_2	D_2	D_2
FlCA	381	533	533	221	309	309
(Beckmann, 1998) [4]	381	533	533	221	309	309
(Ngo, 1998) [71]	-	-	-	221	-	309
(Kim, 1997) [39]	381	533	533	221	309	309
(Sung, 1997) [82]	381	533	533	-	-	309
(Wang, 1996) [90]	381	533	533	221	309	309
(Ko, 1994) [42]	381	533	536	-	-	310

Table 3.5: Experiment results of the 21-cell system

Case	ACC	CSC	Scenario	Channels	LB	UB	Gap
1	1	5	D_1	381	9.067978e+00	9.517727e+00	4.959742e-02
2	1	7	D_1	533	8.063206e+00	9.517727e+00	1.803899e-01
3	2	7	D_1	533	1.219484e+00	9.517727e+00	6.804717e+00
4	1	5	D_2	221	1.265616e-08	9.947808e+00	7.860052e+08
5	1	7	D_2	309	1.265616e-08	9.947808e+00	7.860052e+08
6	2	7	D_2	309	1.265616e-08	9.947808e+00	7.860052e+08

3.4.2 Primal Heuristics

For comparison purpose, we describe two primal heuristics to solve the same problems with Algorithm *A*. Two sets of experiments are performed to test the efficiency and effectiveness of Algorithm *A*. The first primal heuristic adopts a minimize-blocking-rate approach, denoted as Heuristic *B*. This heuristic is very much like Algorithm *A* except not using Lagrangean relaxation technology. In this heuristic, the sector order is the same as Algorithm *A*'s but the channel order is just following the identifiers of channels (i.e. i=1, 2, 3, …, N).

The second primal heuristic is called modified minimize-blocking-rate approach, denoted as Heuristic *C*. The differentiation between Heuristic *B* and *C* is the channel assignment order. The channel assignment order in Heuristic *C* is the odd channels first and then the even channels. That is, the channel assignment sequence will be i=1, 3, 5, …, $[N/2]\times 2+\lceil N/2-[N/2]\rceil$ and then i=2, 4, 6, …, $[N/2]\times 2$. This modification approach is to consider the ACI effect.

These two kinds of primal heuristics can be summarized in the following heuristic algorithm.

- **Heuristics *B* and *C*:**

Step 1. For Heuristic *B*, sort the channel assignment order by the channel number in ascending order. For Heuristic *C*, the odd channels will be assigned first then the even channels.

Step 2. Initialize iteration counter k=0 and sector counter c=0. Reset the decision variables y_{ij} to zero.

Step 3. For each sector, calculate the blocking rate reduction $g_j\left(E(g_j, n_j + \sum_{i\in F} y_{ij}) - E(g_j, n_j + \sum_{i\in F'} y_{ij} + 1)\right)$ if we assign a new channel i to Sector j. Then sort these values in descending order. This is referred to as sector order.

Step 4. According to the sector order decided in Step 3, we choose the cth sector (denoted its identifier as j) of sector order.

Step 5. According to the channel assignment order in Step 1, choose the kth channel (denoted its identifier as by i) of channel order.

Step 6. Check the capacity constraint (3.2) for Sector j. If Sector j cannot add any channels, go to Step 4.

Step 7. Check the QoS constraint (3.3) for Sector j and channel i. If channel i cannot satisfy the CCI and ACI constraints, go to Step 4.

Step 8. Check the feasibility of this assignment decision to assure this assignment must not violate the QoS constraint of other sectors that had been assigned. If it violates the feasibility condition, go to Step 4.

Step 9. Increase sector counter by $c=c+1$ until $c \geq |C|$. Then go to Step 4.

Step 10.Increase iteration counter by $k=k+1$ until $k \geq N$. And then go to Step 3.

Step 11. For each sector, check the blocking constraint (3.1). If any violation occurs, it means this approach cannot find any feasible solution.

3.4.3 Experiment Environments

In the second group of our test networks, the threshold of call-blocking probability of Sector *j* is set to 3%, CIR (γ_j) is set to 9 dB, attenuation factors are set to 4 and ACI is set to 1/8 times of the CCI (i.e. $\theta = \frac{1}{8}$). The first set of experiments is performed on an omni-directional regular network depicted in Figure 3.2 (a). This network has nine cells that are all constructed by omni-directional antenna and arranged on a 3×3 regular networks. This system is referred to as Scenario I. Table 3.6 lists the traffic requirement of each cell on Scenario I. The existing channels for each cell is zero, which means that Scenario I is a classical channel assignment problem. But considering generic cell configuration, CCI and ACI effect, this kind of symmetric network environment is difficult for using classical channel assignment approaches to find feasible solutions. Each frequency used by any cell will interfere all of the other cells that use the same frequency or the two adjacent frequencies. The strength of interfering frequency depends on the power level of interfering cell and the distance between each other.

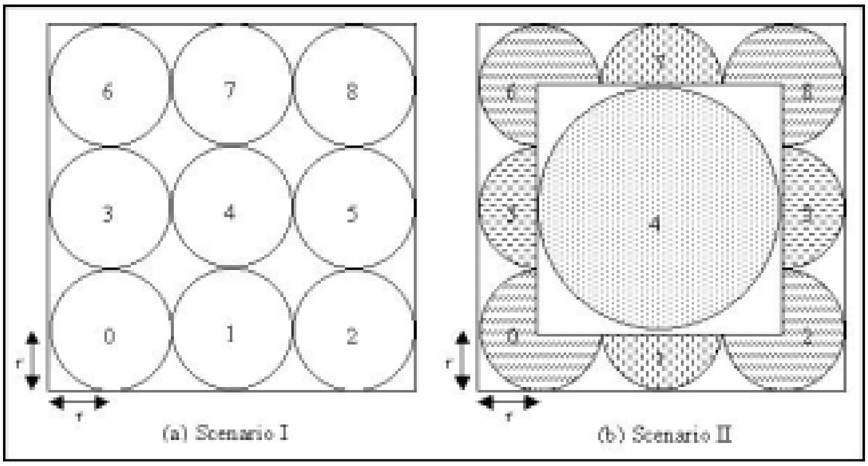

Figure 3.2: The scenarios for computational experiments

Table 3.6: The sector traffic loads on Scenario I

Sector ID	0	1	2	3	4	5	6	7	8
Traffic	30	15	20	18	9	19	27	14	22

3.4.4 Experiment Results

We depicted the experiment results by applying Algorithm *A* in Table 3.7. We can observe that the higher blocking probability often appears at cell 1, 3, 4, 5, or 7. That is because these cells have more neighbors than cell 0, 2, 6 and 8 have. The surrounding neighbors will cause higher interference due to the generic channel interference. We refer to these cells as higher interfered cells and the others as corner cells.

Table 3.7: The computational results of Algorithm *A* on Scenario I

Cases	Average Traffic for each cell	Number of flexible channels	Average call-blocking rate	Maximum blocking probability (cell no.)	Computational time (sec)
1	20	200	N/A	N/A	94
2	20	210	2.528387	0.021051 (1)	98
3	20	220	1.340598	0.012338 (7)	111
4	20	230	0.838419	0.011109 (3)	121
5	20	240	0.468192	0.005817 (4)	131
6	20	250	0.220799	0.005817 (4)	142
7	20	260	0.100974	0.001372 (4)	161

The experiment results show that Algorithm *A* can find feasible solutions with fewer channels than Heuristic *B* and *C* can. Our objective of the channel assignment algorithm is to maximize its reuse factor. We observe that using Heuristic *B* cannot find any feasible solution under the ACI effect. That is, once the previous channel has been assigned to one of the corner cells (i.e. cell number 0, 2, 6 and 8), the following channel will be assigned to the diagonal corner cells due to ACI effect. It makes these channels unable to be assigned to higher interfered cells (i.e. cell 1, 3, 4, 5 and 7). For example, if channel 1 has been assigned to cell 0, it may also be assigned to cell 2, 6, or 8 for maximum reuse factor purpose. We assume that channel 1 has been assigned to cell 0 and 6 for example. Channel 2 will be assigned to cell 2 and 8 for satisfying ACI constraint. Then channel 3 will be assigned to cell 0 and 6. Throughout this channel assignment process, cell 1, 3, 4, 5 and 7 will violate the threshold of blocking probability constraint. That is the reason that we do not discuss the experiment results of Heuristic *B* in this section.

By applying Algorithm *A* and Heuristic *C* on Scenario I, the number of channels needed in feasible solutions is 210 and 270, respectively. We list the comparison in Table 3.8. In the computational experiments, we increase the number of available channels to observe the improvement curve and observe that Algorithm *A* achieves up to 99.4% improvement of the total call-blocking rate against Heuristic *C*.

The second set of experiments is performed on a generic sectorization network, referred to as Scenario II. It is a flexible channel assignment problem with nine cells located on a 3×3 regular networks and depicted in Figure 3.2 (b). The traffic requirements, cell configurations and the existing spectrum usage statuses are listed in Table 3.9. The traffic requirements in Scenario II are derived from it in Scenario I. The quantity of traffic requirement is in direct proportion with the measure of cell coverage area. Table 3.10 is the comparison of results of using Algorithm *A* and Heuristic *C*. The minimum numbers of required flexible channels for Algorithm *A* and Heuristic *C* to find feasible solutions are 175 and 190, respectively. In the computational experiments, Algorithm *A* can achieve up to 58.15% improvement of the total call-blocking rate from Heuristic *C*.

Table 3.8: Comparisons between Algorithm *A* and Heuristic *C*.

No. of channels	*Algorithm A*	*Heuristic C*	Improvement (C-A)/C *100%
260	0.100974	N/A	N/A
270	0.042867	1.069263	95.991020%
280	0.024608	0.670766	96.331327%
290	0.017490	0.402328	95.652869%
300	0.003660	0.229433	98.404832%
310	0.001758	0.137360	98.719889%
320	0.000555	0.071804	99.227376%
330	0.000249	0.043266	99.423746%

Table 3.9: Cell configuration and spectrum usage status on Scenario II

Sector ID	Traffic	Radius (r_j)	Angular (θ_1, θ_2)	No. of existing channels	Initial call-blocking probability	Adjacent situation
0	21	1	(90^0, 360^0)	10	0.557573	(1, 0)
1	11	1	(180^0, 360^0)	11	0.597423	(0, 1)
2	19	1	(180^0, 450^0)	7	0.656617	(0, 0)
3	11	1	(90^0, 270^0)	6	0.522736	(0, 0)
4	57	1.9	(0^0, 360^0)	20	0.657917	(1, 1)
5	11	1	(270^0, 450^0)	3	0.753681	(0, 0)
6	21	1	(0^0, 270^0)	9	0.600123	(0, 1)
7	10	1	(0^0, 180^0)	2	0.819672	(0, 0)
8	18	1	(270^0, 540^0)	8	0.589929	(1, 0)

3.5 Concluding Remarks

In this chapter, we study the FlCA problem in wireless communication networks where the total call-blocking rate is set to be the key performance indicator. In addition, irregular rather than regular cell configuration and sectorization is considered. We formulate this problem as an integer-programming problem and apply Lagrangean relaxation as the basic approach to the algorithm development. We develop an LR-based algorithm and two primal heuristics in this chapter. In computational experiments, the proposed algorithm can find the optimal solution of all six scenarios of the benchmark network. When deal with our two test networks, the proposed algorithm is shown to be far superior to two sensible heuristics. It can find feasible solutions with less number of channels and achieve up to 99.42% and 58.15% improvements of the total call-blocking rate.

Table 3.10: Comparisons among Algorithm *A* and Heuristic *C* on Scenario II

Cases	No. of required flexible channels	Algorithm *A*	Heuristic *C*	Improvement (*C*-*A*)/*C**100%
1	175	4.102679	N/A	N/A
2	180	3.147246	N/A	N/A
3	190	1.776683	2.997904	40.735827%
4	200	1.103023	1.983875	44.400549%
5	210	0.736706	1.134674	35.073317%
6	220	0.307215	0.607275	49.410866%
7	230	0.164812	0.321030	48.661436%
8	240	0.095059	0.156660	39.321226%
9	250	0.045379	0.072155	37.108646%
10	260	0.014411	0.034439	58.155336%
11	270	0.009080	0.015219	40.336120%
12	280	0.004746	0.005962	20.392067%

4. Sequential Homing Problem

In this chapter, we study the problem of sequential homing problem for multiple-connectivity wireless communication networks. In general, there is a trade-off between QoS, the implementation complexity of admission control and system performance. Under the assumption of given average traffic demands and candidate homes for each MT, we propose a generic sequential homing algorithm to determine realtime homing sequence for reliable multiple-connectivity networks to optimize total system call-blocking rate.

The emphasis of this work is to develop a centralized sequential homing policy to decide realtime homing sequence for optimizing total revenue of wireless networks purpose. We formulate this algorithm as a combinatorial optimization problem, where the objective function is to minimize the average system call-blocking rate. For considering generalization, we generalize this sequential homing problem as a sequential routing problem. We model each MT-BS-MTSO (mobile telephone switching office) relationship as one path of MT-MTSO communication pair. Therefore, the problem is to decide the routing sequence for each origin-destination (O-D) pair to optimize system performance by predicting aggregated traffic of each link and blocking probability of each O-D pair. In the computational experiments, we compare the proposed algorithm with the shortest-based heuristic on GTE network. The proposed algorithm can achieve up to 99.98% improvement of the total call-blocking rate.

4.1 Introduction

For supporting reliable wireless communication network, system designer must well deploy BSs and arrange enough spectrum resource to ensure individual connectivity requirement [76]. In this chapter, we model wireless communication networks as virtual circuit networks to accommodate different communication systems by assuming that (1) traffic behaves as Poisson arrival process, (2) Erlang-B formula is used to model virtual circuit networks and (3) average traffic load is used to estimate realtime traffic load.

This sequential homing algorithm can be applied to networks with a sequential and dynamic homing scheme where the homing decisions are updated periodically [79]. That is, the homing sequence for each MT location is updated periodically, with period ΔT. At each update, the candidate homes for each MT are ranked in a preference order. A minimum of one and a maximum of K homes are selected. Until the next update, the homing rule consists in attempting the corresponding homing sequence most recently selected [85].

In this chapter, we propose a sequential routing algorithm to decide realtime homing sequence for reliable multiple-connectivity wireless networks. We decide the routing sequence for each O-D pair to optimize system performance by predicting aggregated traffic of each link and blocking probability of each O-D pair. The emphasis of this work is to develop a centralized sequential routing policy to support resource allocation and management for optimizing long-term system revenue in wireless networks. That is, we apply the proposed sequential routing algorithm as our kernel and combine with FCA mechanism to support realtime admission control for reliable wireless networks [50] [51].

The rest of this chapter is organized as follows. Section 4.2 provides the problem description, the notation definitions and problem formulation. In Section 4.3, we adopt Lagrangean relaxation as our solution approach to deal with this problem. We also develop two algorithms to optimally solve two subproblems. In Section 4.4, several computational experiments will be performed to verify the proposed algorithm. Finally, we conclude this problem in Section 4.5.

4.2 Sequential Routing Problem

A set of admissible homes for a call is tried in a given sequence, and the call is either carried on the first available home encountered in this sequence, or is blocked and cleared from the network if all the homes are busy.

Our sequential routing algorithm adopts the well-known DR5 criterion. The DR5 is the dynamic sequential routing scheme based on 5-minute updates of state-information. That is because a central routing controller maintains a list of admissible paths for all O-D pairs. Link occupancies (collected by scans at 100-second intervals) are reported to the controller at 5-minute intervals. The DR5 routing sequences, based on average or expected link-conditions in the network under statistical equilibrium rather than on instantaneous state-information, would be useful in this routing scheme [43]. The routing sequences are update at 5-minute intervals based on average link-occupancies in the preceding 5-minute period.

4.2.1 Problem Description

In this section, we intend to establish a model to discuss sequential routing problem for generic wireless communication networks. We study how multiple-connectivity property will influence the routing policy and communication GoS. We develop a mathematical model to deal with sequential routing problem in order to minimize total call-blocking rate in the system.

The system parameters are: (1) candidate set of O-D pairs, (2) candidate paths for each O-D pair, (3) the mean arrival rate of new traffic for each O-D pair and (4) the capacity of each link. The objective function of this formulation is to minimize the total call-blocking rate of system subject to: (1) single route constraint and (2) sequential routing constraint. We assume that (1) all paths for each O-D pair are link disjoint, (2) link call-blocking probability is independent from others, (3) overflow traffic also behaves as Poisson arrival process, (4) use Erlang-B formula to model virtual circuit system and (5) average traffic load is used to estimate realtime traffic load. We depict the given parameters in Table 4.1 and the decision variables in Table 4.2.

Table 4.1: Given parameters for sequential routing algorithm

Given Parameters	
Notation	**Description**
$E(n_l, g_l)$	blocking probability of link *l* which is a function of traffic demand g_l and link capacity n_l
P_w	the set of paths which can support requirement of OD pair *w*
L	the set of links
S	the set of permutations which are integer values
W	the set of O-D pairs
e_{pl}	indicator function which is 1 if link *l* belongs to path *p* and 0 otherwise
$\overline{g_l}$	upper bound of aggregate traffic for link *l*
n_l	capacity assigned for link *l*
β_w	the upper bound of call-blocking probability for each O-D pair
λ_w	the mean arrival rate of new traffic for each O-D pair $w \in W$

Table 4.2: Decision variables for sequential routing algorithm

Decision Variables	
Notation	**Description**
B_{ws}	call-blocking probability for the *i*th candidate path for $w \in W$ which belongs to discrete set $B_{ws} \in K_{ws} = \{0, 0.01, 0.02, ..., \overline{B}_{ws}\}$
b_{wl}	blocking probability of link *l* which is referenced by O-D pair *w*
g_l	aggregate flow on link *l* (in Erlang)
x_{ps}	routing decision variable which is 1 if path $p \in P_w$ is selected as the *s*th candidate path for $w \in W$ and 0 otherwise

4.2.2 Program Formulation

Objective function (IP4.1) [52]:

$$Z_{IP1} = \min \sum_{w \in W} \left(\lambda_w \prod_{s \in S} B_{ws} \right) \tag{IP4.1}$$

subject to:

$$\sum_{p \in P_w} x_{ps} \sum_{l \in L} e_{pl} b_{wl} = B_{ws} \qquad \forall w \in W, s \in S \tag{4.1}$$

$$E(n_l, g_l) = b_{wl} \qquad \forall w \in W, s \in S \tag{4.2}$$

$$\sum_{w \in W} \sum_{p \in P_w} \left(\lambda_w e_{pl} \sum_{s \in S} \left(x_{ps} \prod_{k=1}^{s-1} B_{wk} \right) \right) = g_l \qquad \forall l \in L \tag{4.3}$$

$$\prod_{s \in S} B_{ws} \le \beta_w \qquad \forall w \in W \tag{4.4}$$

$$\sum_{p \in P_w} x_{ps} = 1 \qquad \forall w \in W, s \in S \tag{4.5}$$

$$\sum_{s \in S} x_{ps} \le 1 \qquad \forall w \in W, p \in P_w \tag{4.6}$$

$$x_{ps} = 0 \text{ or } 1 \qquad \forall w \in W, p \in P_w, s \in S \tag{4.7}$$

$$0 \le B_{ws} \le \overline{B}_{ws} \qquad \forall w \in W, s \in S \tag{4.8}$$

$$0 \le b_{wl} \le \bar{b}_{wl} \qquad \forall w \in W, l \in L . \qquad (4.9)$$

The objective is to minimize the call-blocking rate of total system. Constraint (4.1) calculates the call-blocking probability. It is reformulated from the original product form of transmission success probability $\prod_{p \in P_w} \left(1 - x_{ps} \prod_{l \in L} \left(1 - e_{pl} E(n_l, g_l)\right)\right) = B_{ws}$ to become solvable formulation. Constraint (4.2) decomposes the call-blocking probability of link *l* by introducing one additional notation b_{wl}. Constraint (4.3) calculates the aggregate traffic for link *l*. Constraint (4.4) enforces call-blocking probability requirement for each O-D pair. Constraint (4.5) enforces that exact one candidate route must be selected on each routing sequence for each O-D pair *w*. Constraint (4.6) allows the number of candidate path to be larger than the number of routing selection sequence. Constraint (4.7) enforces the integer property of the decision variable x_{ps}. Constraints (4.8) and (4.9) enforces the feasible regions of call-blocking probability B_{ws} and b_{wl}.

4.3 Solution Procedure

The sequential routing problem is a combinatorial integer-programming problem with highly non-convexity product form. In general, this problem is NP-complete [1]. The following lemma specifies the deduction of NP-complete property.

Lemma 4.1: this kind of sequential routing problems is NP-complete

Proof:

Because there are several zero-one decision variables in the inequality constraints of the sequential routing problems (IP4.1), this problem can reduce to one kind of 0-1 integer programming problem. As we know that 0-1 integer programming problem is NP-complete [1], the kind of sequential routing problems is NP-complete.□

We do not expect to develop an optimal algorithm for large-scale problems. Instead, an efficient Lagrangean-based algorithm, which has been successfully adopted to solve many famous NP-complete problems [16], is developed in this section.

4.3.1 Lagrangean Relaxation Method

By using the Lagrangean Relaxation method [15], we relax two complicate constraints. One is non-linear programming problem, which is Constraint (4.2), and the other is signomial problem, which is Constraint (4.3) [62]. After dualizing these complicating constraints, we can construct the following Lagrangean relaxation problem (LR4.1):

Objective function (LR4.1):

$$Z_{LR1}(\mu_{wl}^1, \mu_l^2) = \min \sum_{w\in W}\left(\lambda_w \prod_{s\in S} B_{ws}\right) + \sum_{w\in W}\sum_{l\in L}\mu_{wl}^1\left(E(n_l, g_l) - b_{wl}\right)$$

$$+\sum_{l\in L}\mu_l^2\left(\sum_{w\in W}\sum_{p\in P_w}\left(\lambda_w e_{pl}\sum_{s\in S}\left(x_{ps}\prod_{k=1}^{s-1}B_{wk}\right)\right) - g_l\right) \quad \text{(LR4.1)}$$

subject to: (4.1), (4.4), (4.5), (4.6), (4.7), (4.8) and (4.9).

In this formulation, μ_{wl}^1, μ_l^2 are Lagrange multipliers. To solve this problem, we can decompose (LR4.1) into the following two independent and solvable optimization subproblems.

Subproblem (SUB4.1): (related with decision variables B_{ws}, x_{ps} and b_{wl})

Objective function:

$$Z_{SUB1} = \min \sum_{w\in W}\left(\lambda_w \prod_{s\in S} B_{ws}\right) - \sum_{w\in W}\sum_{l\in L}\mu_{wl}^1 b_{wl} + \sum_{w\in W}\sum_{l\in L}\sum_{p\in P_w}\sum_{s\in S}\left(\mu_l^2\lambda_w e_{pl} x_{ps}\prod_{k=1}^{s-1}B_{wk}\right) \quad \text{(SUB4.1)}$$

subject to: (4.1), (4.4), (4.5), (4.6), (4.7) and

$$\underline{B}_{ws} \le B_{ws} \le \overline{B}_{ws} \qquad \forall w\in W, s\in S, B_{ws}\in K_{ws} \qquad (4.10)$$

$$\underline{b}_{wl} \le b_{wl} \le \overline{b}_{wl} \qquad \forall w\in W, l\in L. \qquad (4.11)$$

Because multiplier μ_l^2 may be positive or negative, this formulation is a signomial geometric programming problem, which is more complex and difficult than polynomial programming one [3][5]. To deal with this problem efficiently, we constrain decision variable B_{ws} to a discrete limited set $K_{ws} = \{\underline{B}_{ws}, \underline{B}_{ws} + 0.01, \underline{B}_{ws} + 0.02, ..., \overline{B}_{ws} - 0.01, \overline{B}_{ws}\}$ by introducing an derived Constraint (4.10) from Constraint (4.8) where notations $\underline{B}_{ws}$ and $\overline{B}_{ws}$ are a sensible lower bound and an upper bound. According to experience, the upper bound $\overline{B}_{ws}$ is determined by (1) an artificial threshold: limit the blocking probability to a sensible upper bound of blocking probability (i.e. 20%) or (2) a worst-case value: calculate the worst-case blocking probability by routing all of the traffic to all of the candidate paths. The lower bound $\underline{B}_{ws}$ can be determined by only routing the traffic of this O-D pair to candidate path.

With regard to the discrete property of B_{ts}, we can exhaustively search for all possible values of B_{ts} for each permutation *s*. Therefore, decision variable b_{wl} can be determined by multiplier μ_{wl}^1 if link *l* is not one candidate link of O-D pair *w*. To improve the solution quality, we introduce an derived Constraint (4.11) from Constraint (4.9) to limit decision variable b_{wl} in sensible region. We can describe this situation by

$$b_{wl} = \begin{cases} \overline{b}_{wl}, & \text{if } \sum_{p \in P_w} \sum_{l \in L} e_{pl} = 0 \text{ and } \mu_{wl}^1 \geq 0 \\ \underline{b}_{wl}, & \text{if } \sum_{p \in P_w} \sum_{l \in L} e_{pl} = 0 \text{ and } \mu_{wl}^1 < 0 \end{cases}$$

If link *l* may be one candidate link of O-D pair, i.e. $\sum_{p \in P_w} \sum_{l \in L} e_{pl} = 1$, we can determine its value by maximizing $\sum_{l \in L} \mu_{wl}^1 b_{wl}$ subject to $\sum_{p \in P_w} x_{ps} \sum_{l \in L} e_{pl} b_{wl} = B_{ws}$. We can decompose this problem into |*W*| independent subproblems, denoted as (SUB4.1*w*) and formulate as follows.

Objective function (SUB4.1*w*):

$$Z_{SUB1w} = \min \lambda_w \prod_{s \in S} B_{ws} - \sum_{l \in L} \mu_{wl}^1 b_{wl} + \sum_{l \in L} \sum_{p \in P_w} \sum_{s \in S} \left(\mu_l^2 \lambda_w e_{pl} x_{ps} \prod_{k=1}^{s-1} B_{wk} \right) \quad \forall w \in W \quad \text{(SUB4.1}w\text{)}$$

subject to: (4.1), (4.4), (4.5), (4.6), (4.7), (4.10) and (4.11).

We can solve each subproblem with the following steps.

Step 1. Initialize variable *minValue*=MAX_VALUE.

Step 2. Select one kind of candidate path sequences, assign the associate decision variable $tempX_{ps}$ to equal one and zero otherwise.

Step 3. Select one feasible set of blocking probability values, which satisfies the feasible region defined by Constraint (4.10), and assign to temporary set $tempSetB$ for each permutation $s \in S$.

Step 4. For each link *l*, we assign $temp\_b_{wl}$ to equal $\bar{b}_{wl}$ if $\sum_{p\in P_w}\sum_{l\in L} e_{pl} = 0$ and $\mu_{wl}^1 \geq 0$. If $\sum_{p\in P_w}\sum_{l\in L} e_{pl} = 0$ and $\mu_{wl}^1 < 0$, we assign $temp\_b_{wl}$ to equal $\underline{b}_{wl}$. Otherwise, try to maximize $\sum_{l\in L}\mu_{wl}^1 b_{wl}$ when all of this kind $temp\_b_{wl}$ satisfy $\sum_{p\in P_w} x_{ps}\sum_{l\in L} e_{pl} b_{wl} = B_{ws}$.

Step 5. Under this certain routing sequence $tempX_{ps}$ and blocking probability set $tempSetB$, calculate the objective value of (SUB4.1*w*). If $tempMin$ is smaller than *minValue*, we assign x_{ps}, b_{wl}, B_{ws} and *minValue* to equal $tempX_{ps}$, $temp\_b_{wl}$, $tempB_{ws}$ and $tempMin$, respectively.

Step 6. Go to Step 3 to exhaustively search other possible set $tempSetB$. If there is not any blocking probability case, go to Step 2 to exhaustively search other routing sequences.

Subproblem (SUB4.2): (related with decision variable g_l)

$$Z_{SUB2} = \min \sum_{w \in W} \sum_{l \in L} \mu_{wl}^1 E(n_l, g_l) - \sum_{l \in L} \mu_l^2 g_l \tag{SUB4.2}$$

subject to:

$$0 \le g_l \le \overline{g}_l \qquad \forall l \in L. \tag{4.12}$$

We add a redundant Constraint (4.12) to improve the solution quality. We decompose this problem into |*L*| independent sub-problems, denoted as (SUB4.2*l*) and formulate as follows.

Objective function (SUB4.2*l*):

$$Z_{SUB2l} = \min -\mu_l^2 g_l + E(n_l, g_l) \sum_{w \in W} \mu_{wl}^1$$

subject to (4.12).

Because c_l is a given parameter, the call-blocking probability function $E(n_l, g_l)$ is a well-known Erlang-B formula that is a convex function of decision variable g_l. If multiple $\sum_{w \in W} \mu_{wl}^1 \ge 0$, problem Z_{SUB2l} becomes a convex function. To minimize objective value, the optimal g_l can be found by using line search technique (e.g. golden section method). Otherwise, if multiple $\sum_{w \in W} \mu_{wl}^1 < 0$, problem Z_{SUB2l} becomes a concave function and the optimal solution will be either $g_l = 0$ or $g_l = \overline{g}_l$. The upper bound $\overline{g}_l$ can be determined by function $E(n_l, g_l) = \overline{b}_{wl}$ where $\overline{b}_{wl}$ is an artificial probability threshold for O-D pair *w* being blocked by its candidate link *l*.

4.3.2 The Dual Problem and the Subgradient Method

According to the weak Lagrangean duality theorem [24], for any μ_{wl}^1 and μ_l^2, $Z_{D1} = \max Z_{LR1}(\mu_{wl}^1, \mu_l^2)$ is a lower bound of Z_{IP1}. The dual problem (D4.1) is then constructed to calculate the tightest lower bound [21].

Let a ($|W|\times|L|+|L|$)-tuple vector χ be a subgradient of problem $Z_{LR1}\left(\mu_{wl}^1,\mu_l^2\right)$. In iteration *k* of the subgradient method, the multiplier vector $\pi=\left(\mu_{wl}^1,\mu_l^2\right)$ is updated by π^{k+1} = $\pi^k+\xi^k\chi^k$. The step size ξ^k is determined by $\xi^k=\varsigma\frac{Z_{IP1}^h-Z_{D1}(\pi_k)}{\left\|\chi^k\right\|^2}$, where Z_{IP1}^h is the primal objective function value from a heuristic (an upper bound of Z_{IP1}) and ς is a constant between zero and two [25][30].

4.3.3 Getting Primal Feasible Solutions

When we use Lagrange relaxation method to solve the problem, we not only get a theoretical lower bound but also get some hints in the process of solving dual problem iteratively [58]. These hints are helpful to get primal feasible solutions. Owing to the complexity of the primal problem, we propose a LR-based algorithm in this section and denote as *LR-based Algorithm*.

■ *LR-based Algorithm*

In this approach, we adopt the coefficient of decision variable x_{ps} in LR dual problem as a hint to initialize routing decisions. We denote the coefficient as $\text{Coef}(x_{ps})=\lambda_w\prod_{k=1}^{s-1}B_{wk}\times\sum_{l\in L}\left(\mu_l^2e_{pl}\right)$. To minimize the objective value, we arrange x_{ps} for each O-D pair in descending order of $\text{Coef}(x_{ps})$ as our initial routing sequence. To tune the routing decision to a better result, we also develop a drop-and-add procedure. We specify the detail in the follows.

Step 1. Arrange all O-D pairs in descending order of the value of coefficient $\text{Coef}(x_{ps})$.

We adopt this O-D pair order as our initial routing policy.

Step 2. Sequentially route the associated traffic into the corresponding path. Then calculate the call-blocking probability.

Step 3. Arrange O-D pairs in descending order of its objective value $\lambda_w \prod_{s \in S} B_{ws}$.

Step 4. Choose the maximum objective value O-D pair as our tuning target and run drop-and-add procedure to exhaustively search all of its possible routing sequence. Then output the best objective value of this routing sequence result.

Step 5. Go to Step 2 to select next target O-D pair and exhaustively search all of its candidate routing sequence again. If all O-D pairs have been tried, go to Step 6.

Step 6. Record the decision of Step 5 as our routing policy and finish this algorithm.

4.4 Computational Experiments

4.4.1 The Proposed Primal Heuristics

For comparison purpose, we develop four primal heuristics to solve the same problems. We apply Dijkstra algorithm to find the first *s* shortest paths for each O-D pair as our candidate path set [6]. We develop four intuitive primal heuristics:

(1) Minimum-matrix approach (*MM*): directly adopts the sequence of path length as our routing sequence to calculate the total call-blocking rate;

(2) Shortest-random approach (*SR*): adopt the shortest path as our first routing sequence and randomly select the second and third routing decision for each iteration;

(3) Full-random approach (*FR*): all of the routing sequences are randomly selected from candidate path set;

(4) Exhaustive-one approach (*EO*): adopt the same drop-and-add procedure in *LR-based Algorithm* to find maximum objective value of O-D pair as our target one and exhaust its possible routing sequence.

4.4.2 The DR5 Algorithm

Denardo and Park have investigated a class of routing schemes ranging from sequential attempts over a set of paths to a state-dependent choice of the 'best' path, when such state-dependent information is available [43]. Proceeding from a Markov-decision formulation of the routing problem, they have derived a formula for the expected value of the state-dependent link 'cost', which represents the conditional expected value of the increase in the number of calls blocked on the link. Thus, their formula gives the average penalty due to the use of the link under equilibrium conditions.

$$Cost_l = E(n_l, g_l) \times \left(\frac{n_l}{1 - E(n_l, g_l)} - g_l \right)$$

The penalty of a multi-link route is the sum of the penalties of the individual links. The cost of attempting a path in sequence *s* is given by

$$Cost_{ws} = (1 - B_{ws}) \times \sum_{p \in P_w} x_{ps} \sum_{l \in L} e_{pl} Cost_l$$

The expected cost of attempting a sequence routes is given by

$$Cost_w = \sum_{s \in S} \left(\prod_{k=1}^{s-1} B_{wk} \right) Cost_{ws}$$

The updated state-information is then used to define the routing sequence for each O-D pair for the next five minutes, according to this iterative algorithm. We denote this DR5-based Markov-decision algorithm as *MD* and describe in the follows [43]:

Step 1. The average occupancy of each link over the previous interval is used to evaluate its current 'cost' and thus the costs of all potential paths for the traffic of each O-D pair are determined.

Step 2. Iterative reroute the O-D pair with maximum expected cost to its candidate paths in ascending order of path cost.

4.4.3 Lagrange Relaxation Based Algorithm

We deal with this sequential routing problem by solving the LR dual problem to find the lower bound and adopt the LR-based approach as our LR-based algorithm to find the upper bound of this problem. We describe the detail of LR-based algorithm as follows.

Step 1. Read network file to construct links, capacity and nodes.

Step 2. Randomly generate required number of O-D pairs. Apply Dijkstra's algorithm to find *s* candidate paths and traffic load. Input the maximum iterations and assign Lagrange relaxation improvement counter to equal 40.

Step 3. According to given multipliers, optimally solve the LR subproblems of SUB1 and SUB2 to get the value of Z_D.

Step 4. According to the LR-based approach, *LR-based Algorithm*, get primal feasible solutions. We denote the result as *LR*. The objective value is denoted as Z_{IP}.

Step 5. If Z_D is larger than Z_D*, we assign Z_D* to equal Z_D as our best lower bound. If Z_{IP} is smaller than Z_{IP}*, we assign Z_{IP}* to equal Z_{IP} as our best upper bound. Otherwise, we minus one from the improvement counter.

Step 6. Adopt subgradient method to calculate the subgradient vector and determine the step size in order to adjust Lagrange relaxation multipliers.

Step 7. Increase iteration counter by one. If interaction counter is over threshold of system or the solution procedure is converged, stop this program and Z_{IP}* is our best feasible solution. Otherwise, go to Step 3 to repeat the next iteration.

4.4.4 Experiment Scenarios

In the computational experiments, we test the proposed algorithms for efficiency and effectiveness. The test network is the GTE network, which contains 12 nodes with 50 directed links and is depicted in Figure 4.1. We randomly generate 50 O-D pairs and apply Dijkstra's algorithm to find the first three minimum-hop paths for each O-D pair. Two average traffic loads of each O-D pair are tested in the experiments, which are 20 Erlangs for light traffic load and 22.5 Erlangs for heavy load. The capacity of each link is 100 trunks in the network. Under an average traffic load environment, we randomly generate four test scenarios with different distributions of 50 O-D pairs, denoted as Run 1 to 4.

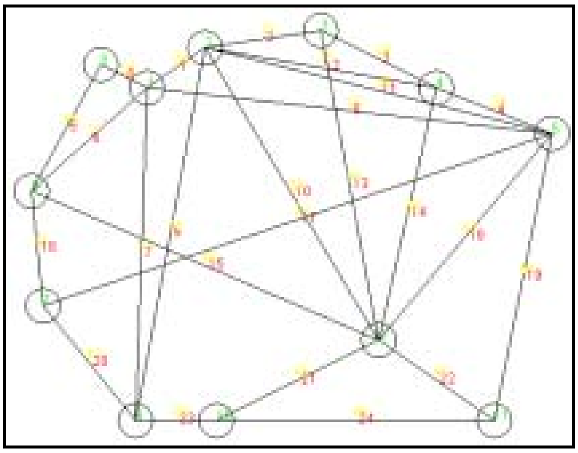

Figure 4.1: The GTE network

4.4.5 Experiment Results

We depict the experiment results of the light traffic load scenarios in Table 4.3 and 4.4 and the results of the heavy traffic load scenarios in Table 4.5 and 4.6. In these experiments, we apply the mentioned four primal heuristics, the *MD* algorithm and the proposed LR-based algorithm on Run 1 to 4. The one routing sequence case (s=1) is not necessary because only the shortest path can be chose for each O-D pair. In Table 4.3 and Table 4.5, we depict the results of five primal heuristics, *MM*, *SR*, *FR*, *EO* and *MD*. We can observe that the results of *EO* or *MD* always achieve better result than others. We can observe that the total system performances of multiple-connectivity cases are greater than that of single connectivity cases. In Table 4.4 and Table 4.6, the proposed *LR* can achieve better system performance than the four primal heuristics. Specifically, although the *MD* is the best primal approach, the proposed

LR-based algorithm *LR* can achieve 99.99 % and 99.45% improvement from the results of the light load and the heavy load cases respectively.

Table 4.3: Experiment results of light traffic load cases by using primal heuristics in the GTE network

λ_w	*S*	Run	*MM*	*SR*	*FR*	*MD*	*EO*	Best
20	2	1	1.5579e-002	1.5579e-002	1.1671e-005	1.5579e-002	2.0062e-003	2.0062e-003
20	2	2	2.4317e-001	2.4317e-001	3.1933e-003	2.4317e-001	5.2602e-003	5.2602e-003
20	2	3	4.7114e-007	4.7114e-007	3.5901e-007	2.7284e-007	1.0327e-007	1.0327e-007
20	2	4	1.5234e-007	1.5234e-007	5.0296e-007	1.5234e-007	1.4957e-007	1.4957e-007
20	3	1	1.9211e-007	5.6989e-009	1.0248e-007	1.4449e-009	7.7259e-015	7.7259e-015
20	3	2	2.7428e-007	2.5818e-008	3.7226e-005	4.0736e-010	9.5396e-009	4.0736e-010
20	3	3	6.1712e-014	6.1712e-014	2.9146e-009	1.1024e-015	1.3498e-015	1.1024e-015
20	3	4	3.1639e-014	3.0002e-014	6.9985e-008	2.3584e-017	1.3055e-015	2.3584e-017

Table 4.4: Light traffic loads for the GTE network using LR approach

λ_w	*S*	Run	Lower Bound	Gap	Best	*LR*	Improvement	Time
20	2	1	4.3783e-007	145.95%	2.0062e-003	1.0768e-006	99.95%	0.162
20	2	2	3.8907e-007	140.51%	5.2602e-003	9.3573e-007	99.98%	0.159
20	2	3	1.7120e-012	3175.09%	1.0327e-007	5.6070e-011	99.95%	0.175
20	2	4	2.2547e-011	667.46%	1.4957e-007	1.7304e-010	99.88%	0.172
20	3	1	2.9080e-016	156.77%	7.7259e-015	7.4669e-016	90.34%	4.77
20	3	2	7.1399e-013	100.00%	4.0736e-010	1.4280e-012	99.65%	4.79
20	3	3	4.9851e-017	100.00%	1.1024e-015	9.9703e-017	90.96%	4.92
20	3	4	5.5041e-019	100.00%	2.3584e-017	1.1008e-018	95.33%	4.92

Table 4.5: Experiment results of heavy traffic load cases by using primal heuristics in the GTE network

λ_w	*S*	Run	*MM*	*SR*	*FR*	*MD*	*EO*	Best
22.5	2	1	3.4390e-001	3.4390e-001	1.2799e-002	3.4390e-001	1.1958e-001	1.1958e-001
22.5	2	2	1.0175e-003	1.0175e-003	3.6781e-004	7.4885e-006	8.1303e-005	7.4885e-006
22.5	2	3	3.6586e-004	3.6586e-004	1.1771e-004	2.5067e-004	7.2006e-005	7.2006e-005
22.5	2	4	9.9639e-005	9.9639e-005	2.0692e-004	9.9639e-005	9.0077e-005	9.0077e-005
22.5	3	1	7.9638e-004	9.2151e-006	1.6411e-003	1.0068e-005	2.4211e-009	2.4211e-009
22.5	3	2	5.1314e-009	3.5635e-009	1.2421e-004	5.8378e-012	9.6663e-012	5.8378e-012
22.5	3	3	7.2319e-007	7.2299e-007	6.0125e-004	5.8560e-011	5.2868e-013	5.2868e-013
22.5	3	4	2.7805e-009	2.7791e-009	7.6242e-005	2.8222e-011	4.2929e-012	4.2929e-012

Table 4.6: Heavy traffic loads for the GTE network using LR approach

λ_w	*S*	Run	Lower Bound	Gap	Best	*LR*	Improvement	Time
22.5	2	1	2.4447e-004	136.63%	1.1958e-001	5.7849e-004	99.52%	0.160
22.5	2	2	8.8340e-008	647.89%	7.4885e-006	6.6068e-007	91.17%	0.165
22.5	2	3	8.8001e-008	1051.87%	7.2006e-005	1.0137e-006	98.59%	0.176
22.5	2	4	3.0805e-007	263.50%	9.0077e-005	1.1197e-006	98.76%	0.166
22.5	3	1	1.1323e-010	100.00%	2.4211e-009	2.2646e-010	90.65%	5.08
22.5	3	2	2.0602e-013	283.47%	5.8378e-012	7.9003e-013	86.47%	4.96
22.5	3	3	6.1958e-014	100.00%	5.2868e-013	1.2392e-013	76.56%	5.04
22.5	3	4	1.5924e-013	100.00%	4.2929e-012	3.1848e-013	92.58%	5.15

4.4.6 Computational Time

All the experiments are performed on a Pentium IV 2.0 GB PC with 1 GB DRAM running Microsoft Windows 2000 Server. The program is implemented by pure C language. Each run is initially performed 1000 iterations to get the best solution. For convergence experiment, we perform 2000 iterations on the test scenario and each experiment only takes about 1500 iterations to converge on the average when the improvement counter is initiated by 40. The computing times per iteration are listed in the last column of Table 4.4 and 4.6.

4.5 Concluding Remarks

To achieve long-term performance optimization, centralized resource allocation and routing arrangement are critical mechanisms for complicate communication systems. In this chapter, we study the key issues of sequential homing problem for multiple-connectivity wireless communication networks about the trade-off between QoS and system performance.

For generalization purpose, we formulate the sequential homing problem as a sequential routing algorithm. Under the assumption of given periodical average traffic demands and candidate routes for each O-D pair, the purpose is to decide realtime connection-setup sequence for reliable multiple-connectivity communication networks. We formulate this algorithm as a combinatorial optimization problem, where the objective function is to minimize the average call-blocking rate in the system.

The emphasis of this work is to develop a centralized sequential homing policy for well-designed multiple-connectivity communication networks. That is, we successfully apply this algorithm as one of our kernels for resource allocation and management in reliable wireless networks. We decide the routing sequence for each O-D pair to optimize system performance by predicting aggregated traffic of each link and blocking probability of each O-D pair. The routing information can be used to combine with admission control, resource allocation, connection setup and QoS assurance. Because this problem is NP-complete, we apply two efficient Lagrangean-based algorithms to solve large-scale problems. In these computational experiments, the proposed Lagrangean-based algorithms achieved up to 99.98% improvement of the total call-blocking rate from the four proposed primal heuristics and the Markov-decision algorithm.

5. Network Planning Module

In this chapter, we identify network-planning issues for channelized wireless communication networks. Due to the time variance and unstable properties of wireless communications, customized multiple connectivity wireless networks are necessary for many kinds of high-reliability communications [68]. By introducing generic communication QoS assurance and concurrently sequential homing mechanisms, we can design a realistic and reliable wireless network.

We formulate this problem as a combinatorial optimization algorithm to design a generic wireless system, which is a multiple-sectorization, power controllable, customized multiple-connectivity and communication QoS assurance network. We integrate long-term channel assignment and sequential homing mechanisms to ensure communication GoS and improve spectrum utilization. The objective function of this formulation is to minimize total cost of network system subject to configuration, capacity, connectivity, sequential homing, QoS and GoS constraints. The solution approach is Lagrangean relaxation. In the computational experiments, our proposed algorithm can achieve up to 36.56% improvement of the total cost of network design problems.

5.1 Introduction

Cellular systems are generally recognized as spectrum-efficient by increasing the frequency allocation, sectorizing the cells and resizing the sectors [49]. In this chapter, we adopt several resource allocation mechanisms such as channel assignment, power control and BS configuration design to optimize total wireless system costs. For modeling generic architecture of realistic networks, we allow each BS to be constructed by any number of sectors, whose radians and transmission powers can be adjusted as needed [54].

Efficient interference management aims at achieving acceptable CIR in all active communication links and optimizing the system capacity. We accumulate CCI, ACI and NCI as total interference and consider the radio propagation characteristic to ensure communication QoS [24] [63]. Furthermore, in order to ensure GoS and support real-time admission control, we develop a location-based sequential homing mechanism to provide multiple-connectivity requirement for each MT [34][57].

We formulate the wireless network design problem as a combinatorial optimization problem, where the objective function is to minimize total cost of system subject to configuration, capacity, connectivity, sequential homing, QoS and GoS constraints. To the best of our knowledge, the proposed algorithm is the first attempt to consider the problem with whole factors jointly and formulate it rigorously. This kind of problems is by nature highly complicated and NP-complete. Thus, we apply the Lagrangean relaxation approach and the subgradient method to solve this problem.

The rest of this chapter is organized as follows. Section 5.2 provides the problem description and mathematical formulation. In Section 5.3, we adopt Lagrangean relaxation as our solution approach. In Section 5.4, we develop several algorithms to get feasible solutions.

Section 5.5 is our computational experiments. Finally, we conclude this problem in Section 5.6.

5.2 Reliable Wireless Network Design Problem

5.2.1 Problem Description

We develop a mathematical model to discuss an integrated wireless communication network design problem, consisting of BS installation, sectorization, capacity allocation, channel assignment, power control and sequential routing problems. We study how multi-configuration sectorization, generic channel interference and terrain-based radio propagation will influence the performance of cellular system. Furthermore, we consider the effects of multiple-connectivity and sequential routing properties to enhance reliability of cellular networks.

We develop a network design model to deal with BS installation, capacity allocation, channel assignment, power control and sequential routing problems. In order to satisfy the QoS level of requirement for each user in the network, we can adjust the configuration/sectorization of each BS, channel assignment policy, power level of each sector and sequential homing policy of each MT to increase resource efficiency. We depict the given parameters in Table 5.1 and the decision variables in Table 5.2. The given parameters are divided into six parts:

(1) BS information: candidate BS locations, available configuration types, capacity limitations and downlink power levels;

(2) MT information: traffic demand, connectivity requirement and location;

(3) System parameters: CIR requirement, receiver sensibility, voice activity and call-blocking rate;

(4) Resource properties: number of available channels and NFD ratio;

(5) Cost functions: channel license, antenna capacity and BS sectorization cost;

(6) Propagation environments: topographical and morphographical data.

Table 5.1: Notation descriptions for given parameters

Notation	Description
A_m	the sector set of configuration $m \in M$
$\overline{B}_{ts}$	upper bound of call-blocking probability for MT *t* on permutation *s*
C	the set of BSs in the system
$E(n_{ja}, g_{ja})$	blocking probability function for Sector a of BS j, which is a Erlang-B formula of traffic demand and available number of channels.
F	the set of available channels
G_{ja}	an arbitrarily large number for Sector a of BS j
K_t	connectivity requirement of MT *t* to connect with K_t candidate homes
ϕ_{tja}	path loss ratio of radio propagation from Sector (j, a) to MT *t*
M	the set of all kinds of sectorization types
N	total number of available channels
S_t	the set of permutation for MT *t* which is integer value and $S_t = \{1, 2, ..., K_t\}$
T	the set of MTs
$\overline{g}_{ja}$	upper bound of aggregate traffic for Sector a of BS j
$\overline{n}_{ja}$	upper bound of channel number for Sector a of BS j
$\overline{p_{ja}}$	upper bound of transmission power of Sector a of BS j
β_t	required GoS of MT *t*

γ	required CIR constraint
$\theta(\Delta i)$	NFD ratio which is formed as a function of the channel separation normalized to the bit-rate
λ_t	the mean traffic arrival rate of MT $t \in T$ (in Erlang)
δ	receiver sensitivity of each MT (in Watt)
Δ_m	cost of BS with configuration type *m*
$\Delta_C(n_{ja})$	capacity cost function of equipments to assign n_{ja} number of channels
Δ_F	spectrum frequency license fee

Table 5.2: Notation descriptions for decision variables

Notation	Description
B_{ts}	call-blocking probability for the s^{th} candidate homing policy for t which belongs to discrete set $B_{ts} \in K_{ts} = \{0,0.01,0.02,..., \overline{B}_{ts}\}$
b_{tja}	blocking probability of Sector a on BS j which is referenced by MT t
c_{jm}	sectorization type m for BS j
f_i	licensed channel
g_{ja}	aggregate flow on Sector a on BS $j \in C$ (in Erlang)
k_{tja}	decision function which is 1 if MT t can be served by Sector a of BS j and 0 otherwise
n_{ja}	number of channels assigned to Sector a of BS j
p_{ja}	effective isotropic radiated power (EIRP) of Sector a on BS j (in Watt)
x_{tjas}	homing decision variable which is 1 if Sector a of BS j is selected as the s^{th} candidate path of MT t and 0 otherwise
y_{ija}	decision variable for channel assignment for Sector (j, a) about Channel i

5.2.2 Problem Formulation

The objective of this formulation is to minimize the total cost of wireless communication network subject to: (1) capacity and configuration constraints of each BS, (2) generic channel interference and QoS constraints, (3) connectivity and sequential homing constraints and (4) call-blocking probability and receiver sensibility constraints for each MT. We develop several algorithms to determine total number of channels required, configuration/sectorization of each BS, transmission power of each sector, channel assignment plan of system, candidate homes of each MT, sequential homing policy and average call-blocking probability under k-connectivity constraints.

Objective function (IP5.1):

$$Z_{IP1} = \min \sum_{j \in C} \sum_{m \in M} \Delta_m c_{jm} + \sum_{j \in C} \sum_{m \in M} \sum_{a \in A_m} \Delta_C \left(n_{ja}\right) + \sum_{i \in F} \Delta_F f_i \tag{IP5.1}$$

subject to:

$$\prod_{s \in S_t} B_{ts} \le \beta_t \qquad \forall t \in T \tag{5.1}$$

$$\sum_{j \in C} \sum_{m \in M} \sum_{a \in A_m} x_{tjas} b_{tja} = B_{ts} \qquad \forall t \in T, s \in S_t \tag{5.2}$$

$$E(n_{ja}, g_{ja}) = b_{tja} \qquad \forall t \in T, j \in C, m \in M, a \in A_m \tag{5.3}$$

$$\sum_{t \in T} \lambda_t \sum_{s \in S_t} \left(x_{tjas} \prod_{k=1}^{s-1} B_{tk} \right) = g_{ja} \qquad \forall j \in C, m \in M, a \in A_m \tag{5.4}$$

$$\gamma \le \frac{\dfrac{p_{ja}}{2\phi_{tja}} \left(y_{ija} + k_{tja}\right) + \left(2 - y_{ija} - k_{tja}\right) G_{ja}}{\displaystyle\sum_{j' \in C - \{j\}} \sum_{m' \in M} \sum_{a' \in A_{m'}} \left(\frac{p_{j'a'}}{\phi_{tj'a'}} \sum_{i' \in F} y_{i'j'a'} \theta(|\, i - i'|) \right)} \qquad \forall t \in T, i \in F, j \in C, m \in M, a \in A_m \tag{5.5}$$

$$k_{tja} \delta \le \frac{p_{ja}}{\phi_{tja}} \qquad \forall t \in T, j \in C, m \in M, a \in A_m \tag{5.6}$$

$$\sum_{j \in C} \sum_{m \in M} \sum_{a \in A_m} x_{tjas} = 1 \qquad \forall t \in T, s \in S_t \tag{5.7}$$

$$\sum_{s\in S_t} x_{tjas} \le k_{tja} \qquad \forall t\in T, j\in C, m\in M, a\in A_m \tag{5.8}$$

$$\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m} k_{tja} \ge K_t \qquad \forall t\in T \tag{5.9}$$

$$\sum_{i\in F} y_{ija} = n_{ja} \qquad \forall j\in C, m\in M, a\in A_m \tag{5.10}$$

$$\sum_{a\in A_m}\left(y_{ija} + y_{(i+1)ja}\right) \le 1 \qquad \forall i\in F, j\in C, m\in M \tag{5.11}$$

$$\sum_{i\in F} f_i \le N \tag{5.12}$$

$$y_{ija} \le f_i \qquad \forall i\in F, j\in C, m\in M, a\in A_m \tag{5.13}$$

$$p_{ja} \le \overline{p}_{ja} \times \sum_{i\in F} y_{ija} \qquad \forall j\in C, m\in M, a\in A_m \tag{5.14}$$

$$y_{ija} \le c_{jm} \qquad \forall i\in F, j\in C, m\in M, a\in A_m \tag{5.15}$$

$$k_{tja} \le c_{jm} \qquad \forall t\in T, j\in C, m\in M, a\in A_m \tag{5.16}$$

$$\sum_{m\in M} c_{jm} = 1 \qquad \forall j\in C \tag{5.17}$$

$$c_{jm} = 0 \text{ or } 1 \qquad \forall j\in C, m\in M \tag{5.18}$$

$$y_{ija} = 0 \text{ or } 1 \qquad \forall i\in F, j\in C, m\in M, a\in A_m \tag{5.19}$$

$$x_{tjas} = 0 \text{ or } 1 \qquad \forall t\in T, s\in S_t, j\in C, m\in M, a\in A_m \tag{5.20}$$

$$k_{tja} = 0 \text{ or } 1 \qquad \forall t\in T, j\in C, m\in M, a\in A_m \tag{5.21}$$

$$f_i = 0 \text{ or } 1 \qquad \forall i\in F \tag{5.22}$$

$$y_{(N+1)ja} = 0 \qquad \forall i\in F, j\in C, m\in M, a\in A_m \tag{5.23}$$

$$0 \le p_{ja} \le \overline{p}_{ja} \qquad \forall j\in C, m\in M, a\in A_m \tag{5.24}$$

$$0 \le n_{ja} \le \overline{n}_{ja} \qquad \forall j\in C, m\in M, a\in A_m. \tag{5.25}$$

The objective function is to minimize the total cost of wireless communication networks, such as costs of (1) fixed installation cost of BSs, (2) capacity equipment cost and (3) the spectrum-licensing fee. These items are the major costs involved in configuring a cellular network. Constraint (5.1) is the acceptable upper bound of call-blocking probability requirement of each MT. Constraint (5.2) is for calculating the call-blocking probability of MT t on the permutation s. Constraint (5.3) decomposes the call-blocking probability of

Sector j by introducing one additional notation b_{tja}. Constraint (5.4) calculates the aggregate traffic for Sector $j \in C$ under sequential routing effect. Constraint (5.5) ensures the CIR constraint for each MT's location. Constraint (5.6) ensures that the received power level is greater than the receiver sensitivity. Constraint (5.7) ensures that one candidate home must be selected on each sequence *s* for each MT. Constraint (5.8) enforces that sequence homes are selected from candidate homes of each MT. Constraint (5.9) enforces the connectivity constraint of MT. Constraint (5.10) calculates the total capacity of channels for each sector. Constraint (5.11) enforce that the adjacent channels should not be assigned to the same BS. Constraints (5.12) and (5.13) ensure that the number of the assigned channels is less than the total channels. Constraint (5.14) ensures that transmission power can be larger than zero only if we have assigned some channels on this sector. Constraint (5.15) ensures that channel can be assigned to this sector only if this configuration is used on BS *j*. Constraint (5.16) ensures that MT can be homed to this sector only if this configuration is used on BS *j*. Constraint (5.17) enforces that only one sectorization type can be selected for each BS. Constraints (5.18) to (5.22) enforce the integer property of the decision variables c_{jm}, y_{ija}, x_{tjas}, k_{tja} and f_i respectively. Constraint (5.23) limits that the boundary variable is not used. Constraints (5.24) and (5.25) enforce the feasible regions of p_{ja} and n_{ja}.

5.3 Solution Procedure

The network-planning problem is an integer-programming problem with highly non-convexity form. In general, this problem is NP-complete [27]. The following lemma specifies the deduction of NP-complete property.

Lemma 5.1: this kind of network-planning problems is NP-complete

Proof:

By adopting problem reduction technique of NP-completeness, the network-planning problem (IP5.1) can be reduced as a generalized channel assignment problem by fixing all decision variables except channel assignment variable y_{ija} as given parameters. As we know that a generalized graph-coloring problem is proved a NP-complete problem [27], the problem (IP5.1) is one kind of generalized graph-coloring problems. That is, the kind of network-planning problems is NP-complete.□

5.3.1 Lagrangean Relaxation Method

In the 1970s [15], Lagrangean methods were used in scheduling and the general integer programming problems. Lagrangean relaxation could provide the proper solutions for those problems. In fact, it had become one of the best tools for optimization problems such as integer programming, linear programming combinatorial optimization and non-linear programming [16]. Lagrangean relaxation has several advantages. For example, Lagrangean relaxation can decompose mathematical models in many different ways and solve by several solution approaches [15][24].

We apply the Lagrange relaxation approach and the subgradient method to solve this problem. Lagrangean relaxation allows us to find out the boundary of our objective function [15]. We can use it to develop efficient heuristics (i.e., algorithms that give solutions that are not guaranteed to be optimal) for getting feasible solutions. Lagrangean relaxation is a flexible solution approach that allows modelers to exploit the underlying structure in any optimization problem by relaxing complicating constraints. This method allows us to “pull apart” models by removing constraints and placing them in the objective function with associated Lagrangean multipliers [24]. The optimal value of the relaxed problem is always a lower bound (for minimization problems) on the objective function value of the problem [15]. To obtain the best lower bound, we need to choose the values of multipliers so that the optimal value of the Lagrangean sub-problem is as large as possible. We can solve the Lagrangean multiplier problem in a variety of ways [21][87]. The subgradient optimization technique is possibly the most popular technique for solving the Lagrangean multipliers problem [25][30].

By using the Lagrangean Relaxation method [15], we can transform the primal problem (IP1) into the following Lagrangean relaxation problem (LR1) where Constraints (5.3), (5.4), (5.5), (5.8), (5.9), (5.10), (5.11) and (5.13) are relaxed.

For a vector of Lagrangean multipliers, a Lagrangean relaxation problem of (IP5.1) is given by optimization problem (LR5.1):

$$
\begin{aligned}
& Z_{LR1}\left(\mu^1_{tjma}, \mu^2_{jma}, \mu^3_{tijma}, \mu^4_{tjma}, \mu^5_t, \mu^6_{jma}, \mu^7_{ijm}, \mu^8_{ijma}\right)= \\
& \min \sum_{j\in C}\sum_{m\in M} c_{jm}\Delta_m + \sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\Delta_C(n_{ja}) + \sum_{i\in F}\Delta_F f_i \\
& +\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\sum_{t\in T}\mu^1_{tjma}\left(E(n_{ja},g_{ja})-b_{tja}\right)+\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\mu^2_{jma}\left(\sum_{t\in T}\lambda_t\sum_{s\in S_t}(x_{tjas}\prod_{k=1}^{s-1}B_{tk})-g_{ja}\right) \\
& +\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\sum_{i\in F}\sum_{t\in T}\mu^3_{tijma}\left(\sum_{j'\in C-\{j\}}\sum_{m'\in M}\sum_{a'\in A_{m'}}\left(\frac{p_{j'a'}}{\phi_{tj'a'}}\sum_{i'\in F}y_{i'j'a'}\theta(|i-i'|)\right)\right) \\
& -\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\sum_{i\in F}\sum_{t\in T}\mu^3_{tijma}\left(\frac{1}{\gamma}(\frac{p_{ja}}{2\phi_{tja}}-G_{ja})(y_{ija}+k_{tja})+\frac{2G_{ja}}{\gamma}\right) \\
& +\sum_{t\in T}\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\mu^4_{tjma}\left(\sum_{s\in S_t}x_{tjas}-k_{tja}\right)+\sum_{t\in T}\mu^5_t\left(K_t-\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}k_{tja}\right) \\
& +\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\mu^6_{jma}\left(\sum_{i\in F}y_{ija}-n_{ja}\right)+\sum_{i\in F}\sum_{j\in C}\sum_{m\in M}\mu^7_{ijm}\left(\sum_{a\in A_m}\left(y_{ija}+y_{(i+1)ja}\right)-1\right) \\
& +\sum_{i\in F}\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\mu^8_{ijma}\left(y_{ija}-f_i\right) \qquad \text{(LR5.1)}
\end{aligned}
$$

subject to: (5.1), (5.2), (5.6), (5.7), (5.12), (5.14), (5.15), (5.16), (5.17), (5.18), (5.19), (5.20), (5.21), (5.22), (5.23), (5.24) and (5.25).

In this formulation, μ^1_{tjma}, μ^2_{jma}, μ^3_{tijma}, μ^4_{tjma}, μ^5_{t}, μ^6_{jma}, μ^7_{ijm}, μ^8_{ijma} are Lagrange multipliers and $\mu^3_{tijma}, \mu^4_{tjma}, \mu^5_{t}, \mu^7_{ijm}, \mu^8_{ijma} \ge 0$ are non-negative integers. To solve (LR5.1), we can decompose it into the following four independent solvable optimization sub-problems and develop several algorithms to optimally solve them in order to determine configuration of each BS, transmission power of each sector, channel assignment plan of system, sequential homing policy of each MT and average call-blocking rate under multiple-connectivity constraints.

Subproblem (SUB5.1): (related with decision variables B_{ts}, b_{tja} and x_{tjas})

$$Z_{SUB1} = \min \sum_{t\in T}\sum_{s\in S}\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m} x_{tjas}\left(\mu^2_{jma}\lambda_t \prod_{k=1}^{s-1} B_{tk} + \mu^4_{tjma}\right) - \sum_{t\in T}\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m} \mu^1_{tjma} b_{tja} \tag{SUB5.1}$$

subject to: (5.1), (5.2), (5.7), (5.20) and

$$\sum_{s\in S_t} x_{tjas} \le 1 \qquad \forall t\in T, j\in C, m\in M, a\in A_m \tag{5.26}$$

$$\underline{B}_{ts} \le B_{ts} \le \overline{B}_{ts} \qquad \forall t\in T, s\in S_t, B_{ts}\in K_{ts} \tag{5.27}$$

$$0 \le b_{tja} \le 1 \qquad \forall t\in T, j\in C, m\in M, a\in A_m. \tag{5.28}$$

Because multiplier μ^2_{jma} is not required to be positive, this formulation is a signomial geometric programming problem, which is more complex and difficult than polynomial programming one [74]. To deal with this problem efficiency, we limit variable B_{ts} to a discrete set $K_{ts} = \{\underline{B}_{ts}, \underline{B}_{ts}+0.01, \underline{B}_{ts}+0.02, ..., \overline{B}_{ts}-0.01, \overline{B}_{ts}\}$ by introducing an Constraint (5.27) where notations $\underline{B}_{ts}$ and $\overline{B}_{ts}$ are a sensible lower bound and upper bound. Considering the discrete property of B_{ts}, we can exhaustively search for all possible values of B_{ts}. According to experience, the upper bound $\overline{B}_{ts}$ is determined by (1) an artificial threshold: limiting the blocking probability to a sensible upper bound of blocking probability (i.e. 20%) or (2) a worst-case value: calculating the worst-case blocking probability by routing all users' traffic to all candidate homes. The lower bound $\underline{B}_{ts}$ can be determined by only routing the traffic of this MT to candidate home.

Without loss generality, we introduce Constraint (5.26) that is implied from Constraints (5.8) and (5.21) to keep physical meaning of decision variable x_{tjas}. Considering the discrete property of B_{ts}, we exhaustively search for all possible values of B_{ts}. To improve the solution quality, we introduce an additional Constraint (5.28) to limit decision variable b_{tja} in feasible region. Therefore, we can decompose this problem into |*T*| independent sub-problems. Each subproblem solves the following problem (SUB5.1*t*),

$$Z_{SUB\,1t} = \min \sum_{s\in S_t}\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m} x_{tjas}\left(\mu^2_{jma}\lambda_t\prod_{k=1}^{s-1}B_{tk} + \mu^4_{tjma}\right) - \sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\mu^1_{tjma}b_{tja}$$

subject to: (5.1), (5.2), (5.7), (5.20), (5.26), (5.27) and (5.28).

We define $\text{Coef}\,(x_{tjas}) = \mu^2_{jma}\lambda_t\prod_{k=1}^{s-1} tempB_{tk} + \mu^4_{tjma} + \mu^1_{tjma}\left(b_{tja} - tempB_{ts}\right)$ as the coefficients of x_{tjas}. Decision variable b_{tja} can be determined by the following

$$b_{tja} = \begin{cases} 1, & \text{if } \sum_{s\in S_t} x_{tjas} = 0 \text{ and } \mu^1_{tjma} \ge 0 \\ 0, & \text{if } \sum_{s\in S_t} x_{tjas} = 0 \text{ and } \mu^1_{tjma} < 0 \\ B_{ts}, & \text{if } \sum_{s\in S_t} x_{tjas} = 1 \end{cases}$$

where the assignment purpose is to minimize the objective value under a given combinatorial situation of x_{tjas} and B_{ts}. In order to minimize this subproblem, we assign the $|S_t|$ number of smallest $\text{Coef}(x_{tjas})$ of x_{tjas} to equal one. That is, we use $|S_t|$ number of $\mu^2_{jma}\lambda_t\prod_{k=1}^{s-1}B_{tk} + \mu^4_{tjma} - \mu^1_{tjma}B_{ts}$ to substitute the responded $\begin{cases} -\mu^1_{tjma}, & \text{if } \mu^1_{tjma} \ge 0 \\ 0, & \text{if } \mu^1_{tjma} < 0 \end{cases}$ in order to minimize the objective value of this subproblem. We develop the following steps to solve this subproblem.

Step 1. Initialize variable *minValue*=MAX_VALUE.

Step 2. Select one feasible set of blocking probability values, which satisfies the feasible region defined by Constraints (5.1) and (5.27), and assign to temporary set

$tempSetB$ for each permutation $s \in S_t = \{1,2,...,K_t\}$. Let $passedSector = \{\}$ and $remainingSector = \{\text{all pairs of } (BSId, SectorId)\}$.

Step 3. Under a certain call-blocking probability set, we arrange the homing decision variable $tempX_{tjas}$ in ascending order of its coefficient value $\text{Coef}(x_{tjas})$.

Step 4. For each permutation $s \in S_t = \{1,2,...,K_t\}$, we assign the smallest $tempX_{tjas}$ to equal 1 if Sector (j, a_m) belongs to set $remainingSector$. To satisfy Constraints (5.7) and (5.26), we remove this sector (j, a_m) from set $remainingSector$ and insert it into the other set $passedSector$.

Step 5. For each sector (j, a_m), we assign $temp\_b_{tja}$ to equal $tempB_{ts}$ if Sector (j, a) belongs to set $passedSector$. We assign $temp\_b_{tja}$ to equal 1 if $\mu^2_{tjma} \geq 0$ and 0 otherwise.

Step 6. Under this certain $tempSetB$, calculate the objective value by $tempMin =$ $\sum_{s\in S_t}\sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m} tempX_{tjas} \times \left(\mu^2_{jma}\lambda_t \prod_{k=1}^{s-1} tempB_{tk} + \mu^4_{tjma} \right) - \sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m} \mu^1_{tjma} \times temp\_b_{tja}$. If $tempMin$ is smaller than $minValue$, we assign x_{tjas}, b_{tja}, B_{ts} and $minValue$ to equal $tempX_{tjas}$, $temp\_b_{tja}$, $tempB_{ts}$ and $tempMin$, respectively.

Step 7. Go to Step 2 to exhaustively search other possible power set $tempSetB$.

Subproblem (SUB5.2): (related with decision variables g_{ja} and n_{ja})

$$Z_{SUB2} = \min \sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m} \left(\Delta_C(n_{ja}) + \sum_{t\in T} \mu^1_{tjma} E(n_{ja}, g_{ja}) - \mu^2_{jma} g_{ja} - \mu^6_{jma} n_{ja} \right) \tag{SUB5.2}$$

subject to: (5.25) and

$$0 \leq g_{ja} \leq \overline{g}_{ja} \qquad \forall j \in C, m \in M, a_m \in A. \tag{5.29}$$

We add a redundant Constraint (5.29) to improve the solution quality. We decompose this problem into |*C*|×|*M*|×|*A*| independent sub-problems. Each subproblem solves the following problem (SUB5.2*jma*),

$$Z_{SUB2jma} = \min \Delta_C(n_{ja}) + \sum_{t\in T} \mu^1_{tjma} E(n_{ja}, g_{ja}) - \mu^2_{jma} g_{ja} - \mu^6_{jma} n_{ja}$$

subject to: (5.25) and (5.29).

Because decision variable n_{ja} is a positive and limited integer, we can exhaustively search n_{ja} from zero to $\overline{n}_{ja}$. When give a certain value of n_{ja}, the call-blocking probability term $E(n_{ja}, g_{ja})$ is a convex function of decision variable g_{ja}. If multiple $\mu^1_{tjam} \geq 0$, problem $Z_{SUB2jam}$ becomes a convex function. To minimize objective value, the optimal g_{ja} can be found by using line search technique (e.g. golden section method). Otherwise, if multiple $\mu^1_{tjma} < 0$, problem $Z_{SUB2jam}$ becomes a concave function and the optimal solution will occur either $g_{ja} = 0$ or $g_{ja} = \overline{g}_{ja}$. The upper bound $\overline{g}_{ja}$ can be determined by function $E(\overline{n}_{ja}, g_{ja}) = \overline{b}_{tja}$ where $\overline{b}_{tja}$ is an artificial probability threshold for MT *t* being blocked by its candidate home.

Subproblem (SUB5.3): (related with decision variables c_{jm}, k_{tja}, p_{ja} and y_{ija})

$$Z_{SUB3} = \min \sum_{j\in C}\sum_{m\in M} \Delta_m c_{jm} - \sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\sum_{t\in T} k_{tja}\left(\mu^4_{tjma} + \mu^5_t + \frac{1}{\gamma}\left(\frac{p_{ja}}{2\phi_{tja}} - G_{ja}\right)\sum_{i\in F}\mu^3_{tijma}\right)$$
$$+ \sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\sum_{i\in F} y_{ija} \sum_{t\in T}\left(\frac{\mu^3_{tijma} G_{ja}}{\gamma} - \frac{p_{ja}}{\phi_{tja}}\frac{\mu^3_{tijma}}{2\gamma} + \frac{p_{ja}}{\phi_{tja}} \sum_{j'\in C-\{j\}}\sum_{m'\in M}\sum_{a'\in A_{m'}}\sum_{i'\in F} \mu^3_{ti'j'm'a'} \theta(|i'-i|)\right)$$
$$+ \sum_{j\in C}\sum_{m\in M}\sum_{a\in A_m}\sum_{i\in F} y_{ija}\left(\mu^6_{jma} + \mu^7_{(i-1)jm} + \mu^7_{ijm} + \mu^8_{ijma}\right) \quad \text{(SUB5.3)}$$

subject to: (5.6), (5.14), (5.15), (5.16), (5.17), (5.18), (5.19), (5.21), (5.24) and

$$\sum_{i\in F} y_{ija} \leq \overline{n}_{ja} \qquad \forall j\in C, m\in M, a_m \in A \qquad (5.30)$$

$$\mu^7_{0j} = 0 \qquad \forall j\in C, m\in M, a_m \in A. \qquad (5.31)$$

Without loss generality, we add an additional Constraint (5.30) to improve quality of solutions. To aggregate decision variable y_{ija}, we reformulate this subproblem by removing Constraint (5.23) and introducing an additional Constraint (5.31).

Constraints (5.17) and (5.18) ensure that there is only one kind of sectorization that can be deployed for each BS. Furthermore, Constraints (5.14) and (5.15) enforce that only the sectors belonging to selected configuration type can be assigned channels and transmission power. Therefore, we decompose this problem into |*C*| independent subproblems (SUB5.3*j*) and exhaustively search any kind of configuration c_{jm} for each BS. After a temporary configuration $tempC_{jm}$ is determined, we can decompose the remaining problem into |*C*|×|*M*|×|*A*| subproblems (SUB5.3*jma*) as follows.

$$
\begin{aligned}
Z_{SUB\,3\,jma} = \min\ & -\sum_{t\in T} k_{tja}\left(\mu^4_{tjma} + \mu^5_t + \frac{1}{\gamma}\left(\frac{p_{ja}}{2\phi_{tja}} - G_{ja}\right)\sum_{i\in F}\mu^3_{tijma}\right) \\
& + \sum_{i\in F} y_{ija}\sum_{t\in T}\left(\frac{\mu^3_{tijma}G_{ja}}{\gamma} - \frac{p_{ja}}{\phi_{tja}}\frac{\mu^3_{tijma}}{2\gamma} + \frac{p_{ja}}{\phi_{tja}}\sum_{j'\in C-\{j\}}\sum_{m'\in M}\sum_{a'\in A_{m'}}\sum_{i'\in F}\mu^3_{ti'j'm'a'}\theta(|i'-i|)\right) \\
& + \sum_{i\in F} y_{ija}\left(\mu^6_{jma} + \mu^7_{(i-1)jm} + \mu^7_{ijm} + \mu^8_{ijma}\right) \qquad \text{(SUB5.3}jma\text{)}
\end{aligned}
$$

subject to: (5.6), (5.14), (5.15), (5.16), (5.19), (5.21), (5.30) and (5.31).

For each Sector (j,a), we can exhaustively search candidate transmission power p_{ja} from zero to $\overline{p}_{ja}$. To determine the remaining decision variables y_{ija} and k_{tja}, we denote the coefficients of k_{tja} and y_{ija} as $\text{Coef}(k_{tja})$ and $\text{Coef}(y_{ija})$ respectively. Their definitions are $\text{Coef}(k_{tja}) = \mu^4_{tjma} + \mu^5_t + \frac{1}{\gamma}\left(\frac{p_{ja}}{2\phi_{tja}} - G_{ja}\right)\sum_{i\in F}\mu^3_{tijma}$ and $\text{Coef}(y_{ija}) =$

$$
+\sum_{t\in T}\left(\frac{\mu^3_{tijma}G_{ja}}{\gamma} - \frac{p_{ja}}{\phi_{tja}}\left(\frac{\mu^3_{tijma}}{2\gamma} - \sum_{j'\in C-\{j\}}\sum_{m'\in M}\sum_{a'\in A_{m'}}\sum_{i'\in F}\mu^3_{ti'j'm'a'}\theta(|i'-i|)\right)\right) + \mu^6_{jma} + \mu^7_{(i-1)jm} + \mu^7_{ijm}
$$

$+\mu^{8}_{ijma}$. Therefore, we can arrange the contribution of each decision variable to minimize Subproblem (SUB5.3*jma*).

We can solve this subproblem (SUB5.3*jma*) with the following steps.

Step 1. Initialize minValue=MAX_VALUE

Step 2. To solve (SUB5.3), we select one type of sectorization configuration for each BS and assign the correspond variable $tempC_{jm}$ to equal one.

Step 3. To solve (SUB5.3*jma*), we exhaust search any feasible transmission power level and assign to temporary variable $tempP_{ja}$ for Sector (j,a).

Step 4. For homing purpose, we calculate $\text{Coef}(k_{tja})$ for each Sector (j,a) and sort $tempK_{tja}$ in descending order of $\text{Coef}(k_{tja})$.

Step 5. For minimizing objective value purpose, we assign $tempK_{tja}$ to equal one if $\text{Coef}(k_{tja}) \geq 0$ and Constraint (5.6) is feasible. Otherwise, we assign $tempK_{tja}$ to become zero.

Step 6. For channel assignment purpose, we calculate $\text{Coef}(y_{ija})$ for each channel i and arrange the channels in ascending order of $\text{Coef}(y_{ija})$.

Step 7. For minimizing objective value purpose, we assign $tempY_{ija}$ to one if $\text{Coef}(y_{ija}) < 0$ and $\sum_{i\in F} tempY_{ija} \leq \bar{n}_{ja}$. Otherwise, we assign $tempY_{ija}$ to zero.

Step 8. Calculate the temporary objective value under the power set *tempSetP* by $tempMin = \sum_{i\in F}\left(tempY_{ija} \times \text{Coef}(y_{ija})\right) - \sum_{t\in T}\left(tempK_{tja} \times \text{Coef}(k_{tja})\right)$. If *tempMin* smaller than *minValue*, we assign c_{jm}, k_{tja}, p_{ja}, y_{ija} and *minValue* to equal $tempC_{jm}$, $tempP_{ja}$, $tempY_{ija}$, $tempK_{tja}$ and $tempMin$, respectively.

Step 9. If there is any possible power level that has not been tried, go to Step 3 to exhaustively search other possible power $tempP_{ja}$. Otherwise, go to Step 2 to try other configuration types.

Subproblem (SUB5.4): (related with decision variables f_i)

$$Z_{SUB\ 4} = \min \sum_{i \in F} f_i \left(\Delta_F - \sum_{j \in C} \sum_{m \in M} \sum_{a \in A_m} \mu^8_{ijma} \right) \quad \text{(SUB5.4)}$$

subject to: (12), (21) and

$$\underline{F} \le \sum_{i \in F} f_i \le \overline{F} . \quad (5.32)$$

According to experience, we intend to find the lower bound $\underline{F}$ and upper bound $\overline{F}$ of $\sum_{i \in F} f_i$ to improve efficiency and quality of both dual and primal solutions for this subproblem. Therefore, we enhance the effect of Constraint (5.12) by introducing additional Constraint (5.32). Upper bound $\overline{F}$ can be the smaller one between the capacity upper bound summation of every BS or the total available channels in the system. However, it is difficult to find tighter lower bound $\underline{F}$ in this subproblem.

We can solve this problem with the following steps.

Step 1. Arrange the channels in ascending order of $\text{Coef}(f_i) = \Delta_F - \sum_{j \in C} \sum_{m \in M} \sum_{a \in A_m} \mu^8_{ijma}$.

Step 2. According to Constraint (5.32), if $\sum_{i \in F} f_i \le \underline{F}$, we assign f_i to equal one. If $\underline{F} < \sum_{i \in F} f_i \le \overline{F}$ and $\text{Coef}(f_i) \le 0$, we assign f_i to equal one. Otherwise, we assign f_i to equal zero.

5.3.2 The Dual Problem and the Subgradient Method

According to the weak Lagrangean duality theorem [15][24], $Z_{D1} = \max Z_{LR1}\left(\mu^1_{tjma}, \mu^2_{jma}, \mu^3_{tijma}, \mu^4_{tjma}, \mu^5_t, \mu^6_{jma}, \mu^7_{ijm}, \mu^8_{ijma}\right)$ is a lower bound on Z_{IP1} for any $\mu^3_{tijma}, \mu^4_{tjma}, \mu^5_t, \mu^7_{ijm}, \mu^8_{ijma} \geq 0$. The following dual problem (D5.1) is then constructed to calculate the tightest lower bound.

Dual Problem (D5.1):

$$Z_{D1} = \max Z_{LR1}\left(\mu^1_{tjma}, \mu^2_{jma}, \mu^3_{tijma}, \mu^4_{tjma}, \mu^5_t, \mu^6_{jma}, \mu^7_{ijm}, \mu^8_{ijma}\right)$$

subject to:

$$\mu^3_{tijma}, \mu^4_{tjma}, \mu^5_t, \mu^7_{ijm}, \mu^8_{ijma} \geq 0$$

In this dual problem, let a ($|C| \times |M| \times \{|A| \times [|T| \times (|F| + 2) + |F| + 2] + |F|\} + |T|$)-tuple vector χ be a subgradient of problem $Z_{LR1}\left(\mu^1_{tjma}, \mu^2_{jma}, \mu^3_{tijma}, \mu^4_{tjma}, \mu^5_t, \mu^6_{jma}, \mu^7_{ijm}, \mu^8_{ijma}\right)$. In iteration k of the subgradient method [25], the multiplier vector $\pi = \left(\mu^1_{tjma}, \mu^2_{jma}, \mu^3_{tijma}, \mu^4_{tjma}, \mu^5_t, \mu^6_{jma}, \mu^7_{ijm}, \mu^8_{ijma}\right)$ is updated by $\pi^{k+1} = \pi^k + \xi^k \chi^k$. The step size ξ^k is determined by $\xi^k = \varsigma \frac{Z^h_{IP1} - Z_{D1}(\pi_k)}{\left\|\chi^k\right\|^2}$, where Z^h_{IP1} is the primal objective function value from a heuristic (an upper bound on Z_{IP1}) and ς is a constant between zero and two [30].

5.4 Getting Primal Feasible Solutions

When we use Lagrangean relaxation method as our solution approach to solve the problem, we not only get a theoretical lower bound of primal solutions but also get some hints in the process of solving dual problem iteratively. Owing to the complexity of the primal problem, a divide-and-conquer strategy is proposed to get the primal feasible solutions. We divide this integrated wireless communication network design problem into three parts: (1) BS configuration subproblem including sectorization type and power control, (2) sequential homing subproblem and (3) channel assignment subproblem. In each subproblem, we provide some heuristics to get primal feasible solutions.

5.4.1 Heuristic *A*: BS Configuration Subproblem

In this subproblem, we refer to the results of decision variables c_{jm}, p_{ja} and k_{tja} that are calculated when solving subproblem (SUB5.3) as our initial values to determine the BS allocation, BS sectorization type, transmission power control and candidate homing decisions. We also develop a drop-and-add procedure to find better feasible solution. The detail of the BS configuration heuristic is described in the following.

First, we deal with the BS allocation and sectorization subproblem. If $c_{j0} = 1$, we consider this BS may not be allocated. Otherwise, let $a_m \in A = \{1,2,...,m\}$ if $c_{jm} = 1$. That is, BS j uses m antennas to construct m sectors in its coverage area. Second, to determine the transmission power, we directly use the results of power level p_{ja} as our primal solutions and then tune the power level to minimize the intercellular interference and to maximize the number of serviced mobiles. Finally, in candidate homing subproblem, we assign the associated k_{tja} to equal one according to the connectivity requirement and the BS coverage situation.

For each mobile violating its connectivity constraint, denoted as violated mobiles, we divide all sectors into five groups, which are home sectors, candidate sectors, enlarge-power sectors, new-deploy sectors and others. Home sectors are those to satisfy the CIR constraint and ready to service for this mobile. Candidate sectors also satisfy the CIR constraint but still do not become one home of this mobile. Enlarge-power sectors violate the CIR constraint but can satisfy this constraint by enlarging its current power level. If none of the first three groups can satisfy the connectivity requirement of violated mobiles, we must deploy new BS, denoted as new-deploy sectors in this heuristic. We describe the detail of the BS configuration heuristic in the following.

Step 1. Directly refer the results of c_{jm}, p_{ja} and k_{tja} from LR5.1 dual problem as our initial configuration type.

Step 2. Considering connectivity constraint, if all mobiles are feasible, go to Step 6. Otherwise, divide all sectors into five groups and apply add-procedure to find a feasible solution. If any candidate sector exists, go to Step 3 to add new home sector. Otherwise, if there is any enlarge-power sector, go to Step 4 to tune power level. Otherwise, go to Step 5 to deploy new BS.

Step 3. Without modifying configuration and power level, we home all of the violated mobiles to its candidate sector in descending order of the value $\text{Coef}(k_{tja})$ calculated in SUB5.3. Then, go to Step 2 for additional process.

Step 4. In order to determine the order of enlarge-power sectors, all of the violated mobiles elect their favors. Then we enlarge the power level of the maximum-vote sector to reason level and then go to Step 2.

Step 5. The deployment decision is decided by vote of the entire infeasible mobiles. We deploy the most favor BS with the maximum-votes configuration and power level. Then, go to Step 2. This new deployment decision must minimize the interference to the existing deployed sectors and maximize the number of serviced mobiles. That is trade-off between configuration selection and power control.

Step 6. Applying drop-procedure to tune all configuration of deployed sector.

5.4.2 Heuristic *B*: Sequential Homing Subproblem

In this subproblem, we determine the decision variables x_{tjas}, B_{ts}, b_{tja} and g_{ja} by referring to the result of B_{ts} and the order of $\text{Coef}(x_{tjas})$ calculated by (SUB5.1). According to the results of candidate homes k_{tja} calculated by *Heuristic A*, we assign the homing sequence in ascending order of $\text{Coef}(x_{tjas})$. Adopt the associated value of B_{ts} as the call-blocking probability b_{tja} of this sector. Then, aggregate partial traffic of the serviced mobiles to determine g_{ja}. We describe the detail of Heuristic *B* in the following.

Step 1. Directly use the sequential call-blocking probability to calculate $\text{Coef}(x_{tjas})$.

Step 2. For each mobile, arrange its home sectors in ascending order of $\text{Coef}(x_{tjas})$ and then assign the homing sequence x_{tjas} to this sector. Note that this assignment decision must satisfy the sequential homing constraint.

Step 3. For each sector, select the minimum associated sequential call-blocking probability as the call-blocking probability of this sector.

Step 4. Following the traffic aggregation constraint, we aggregate the associated traffic of sequential homing mobile to become the aggregate traffic of each sector.

5.4.3 Heuristic *C*: Channel Assignment Subproblem

In this subproblem, we determine the decision variables y_{ija}, f_i and n_{ja} by referring to the result of y_{ija} and the order of $\text{Coef}\left(y_{ija}\right)$ calculated by (SUB5.3). Subject to CIR, adjacent channel and call-blocking probability constraints, we use the Lagrangean relaxation-based (LR-based) channel order and most-capacity- requirement-first sector order to determine the channel assignment decision. That is, we refer the hints of LR dual problem to sort channel order for each sector.

Step 1. For each sector, calculate the value of $\text{Coef}\left(y_{ija}\right)$ as our channel assignment decision. Arrange channel order in descending order of $\text{Coef}\left(y_{ija}\right)$.

Step 2. Calculate the minimum required channels for each sector to satisfy QoS constraint. Arrange sector order in descending order of required channels.

Step 3. For the first sector, which requires the greatest channel capacities, assign the first channel that has the smallest value of coefficient $\text{Coef}\left(y_{ija}\right)$ to this sector if this channel satisfies CIR and adjacent channel constraints. Minus the required capacity of this sector by one

Step 4. If there is no available channel and there is any sector requiring more capacity, we cannot find a feasible solution. Otherwise, go to Step 2.

Step 5. Calculate the assigned capacity n_{ja} for each sector and gather statistics for total used channel f_i in order to calculate license fee.

5.5 Computational Experiments

Owing to the complexity of this problem, we cannot find tighter lower bound by solving dual problem. That is because the cost function plays an important role in affecting the duality gaps of (IP5.1). In order to prove that our LR-based heuristics are good enough, we also implement a primal algorithm to compare with our heuristics.

5.5.1 Primal Algorithm

In previous section, we use some LR-based heuristics to determine (1) BS configuration subproblem, (2) sequential homing subproblem and (3) channel assignment subproblem. Contrarily, we use an intuitive thought to determine them in this primal algorithm. We adopt election policy to determine best BS configuration and sequential homing decisions. That is, all mobiles elect their candidate homes and then we deploy the most voted BS to service the maximum mobile. According to the slave mobiles in each sector, we can determine the transmission power of each sector in order to minimize inter-cell interference. The homing sequence is following the deployment sequence of home sectors. Then, we also apply most-capacity-requirement-first policy as our sector order and solve channel assignment subproblem. For convenience, we denote this algorithm as *PA* and describe it in the following.

Step 1. Initialize transmission power of all sectors to maximum level.

Step 2. To minimize the coverage intersection with existing BSs, we reduce the power level if any mobile, which must not homed to this sector, locates in the coverage of this sector.

Step 3. We adopt election policy to determine the configuration of each BS. Each mobile elects its candidate home with favor configuration. Then, we deploy the most voted BS with the most voted configuration.

Step 4. We simply adopt the BS deployment order as the homing sequence of each mobile. For each sector, aggregate traffic and calculate the corresponding call-blocking probability.

Step 5. Arrange all existing sectors by most- capacity-requirement-first order. Confirm each channel's feasibility by checking the CIR and adjacent channel constraints for each sector. Then, assign required number of feasible channels to each sector.

5.5.2 Lagrangean Relaxation Based Algorithm

When solving Lagrangean relaxation problem, we provide an iterative LR-based algorithm to get primal feasible solutions. In this algorithm, we allow any kind of sectorization configurations to be deployed as our last solution to generic network design problems. In each iteration, we apply Heuristic *A*, *B* and *C* to solve each subproblem and then find a feasible solution. For convenience, we denote it as *LR* and show as follows:

Step 1. Read configuration file to construct terrain data, candidate BSs and existing MTs.

Step 2. Construct configuration information, pre-calculate path loss for each BS-MT pair and predict the success possibility of planning project specifically on connectivity constraints.

Step 3. Calculate constant parameters, initialize Lagrangean multipliers and assign Lagrangean relaxation improvement counter to equal 30.

Step 4. Apply primal algorithm to get a feasible solution. This objective value can be adopted as our initial upper bound of this planning problem.

Step 5. Solve Lagrangean relaxation problem by optimally solving the sub-problems of SUB5.1, SUB5.2, SUB5.3 and SUB5.4 to get the minimum objective value of Z_{LR1} according to given multipliers.

Step 6. Get primal feasible solutions by using LR-based heuristics, which is Heuristic *A*, *B* and *C*. Calculate the total cost of feasible wireless network design as a candidate upper bound of the problem, denoted as Z_{IP1}.

Step 7. If Z_{LR1} is larger than the existing lower bound Z_{LR1}*, we assign Z_{LR1}* to equal Z_{LR1}. If Z_{IP1} is smaller than the existing upper bound Z_{IP1}*, we assign Z_{IP1}* to equal Z_{IP1} and reset the improvement counter. Otherwise, we decrease the improvement counter by one.

Step 8. We calculate the gap between upper bound and lower bound to determine the stop criteria. If the gap is smaller than 5%, we can stop this program and claim that we find the near optimal solution for this planning problem. Otherwise, adopt subgradient method to calculate step size and adjust Lagrangean multipliers.

Step 9. Increase the iteration counter by one. If interaction counter is over maximum iteration of system, stop this program. That is, Z_{IP1}* is our best feasible solution. Otherwise, go to step 5.

5.5.3 Experiment Environments

In practical mobile systems, because the maximum number of sectors for one BS is five and the radian unit of each sector is practically 20^{o}, we can calculate the number of candidate configuration types for each BS and depict in Table 5.3. The major assumptions and parameters used in this study are described in the following subsections.

5.5.3.1 Assumptions

1. In our model, mobiles are concepts of location-based cellular receivers. The mobility of MTs is ignored.
2. We consider path loss and shadowing (or slow fading) propagation effects. However, Multiple-path fading (fast fading) is assumed fixed.
3. We use Erlang-B formula to model telephony communication networks as M/G/m/m queueing systems.

4. Calls arrive according to a Poisson process.
5. The overflow traffic also behaves as Poisson arrival process.
6. Average traffic load is used to estimate realtime traffic load.

Table 5.3: Number of candidate configurations according to maximum number of sectors per BS and the radian unit of each sector

Radian Unit / Max no. of sectors per BS	Unit=20 ^{o}	Unit=30 ^{o}	Unit=40 ^{o}	Unit=45 ^{o}
1 sector/BS	18	12	9	8
2 sectors/BS	171	78	45	36
3 sectors/BS	987	298	129	92
4 sectors/BS	4,047	793	255	162
5 sectors/BS	12,615	1,585	381	218

5.5.3.2 Parameters

The environment parameters are as follows:

1. Available bandwidth is 1.2 MHz.
2. Maximum number of channels, which can be assigned to a sector, is 60.
3. Threshold of acceptable CIR is 9 dB.
4. Maximum call-blocking probability of BSs is 3%
5. Transmission power levels of each sector are 4, 6, 8, 10, 12 and 14 dBW.
6. Sensitivity of received power for each MT is -130 dBW.
7. Fixed cost of a BS equals NT $5,000,000 dollars.
8. Fixed cost of a smart antenna is NT $200,000 dollars.
9. Cost of a transponder, which can serve eight channels, is NT $400,000 dollars.
10. Cost of licensing for one channel is NT $200,000 dollars.

5.5.3.3 Scenarios

In our computational experiments, we generate several system scenarios with different (1) numbers of candidate BSs, (2) numbers of candidate MTs, (3) maximum connectivity requirements and (4) sectorization configurations.

In this case, we have 10 BSs and 10 MTs. The traffic demand for each OD-pairs is 3 Erlangs. Two kinds of connectivity requirements are experimented in this case. Since the numbers of candidate-homes for MTs are different, we explore one-connectivity and three-connectivity requirements as our two scenario groups in this case.

5.5.4 Experiment Results

We generate 10 BSs and 10 MTs as our test network at random. For comparison purpose, we group the experiment results into Table 5.4. To analyze the effect of sectorization, we explore different numbers of sectors in each BS from omni-direction to three sectors with the radian unit being 45^o. We also explore the effect of multiple-connectivity on the total cost of cellular systems. In Table 5.4, we can find with the growth of connectivity requirements, the required number of deployed BSs also grows. As the allowed sector number grows, the required channel of cellular systems is smaller. The multiple-connectivity can improve communication reliability but will spend more deployment cost.

5.5.5 Computational Complexity

We denote the number of BSs, candidate configurations, maximum sectors, MTs, homing sequences, available channels and candidate power levels as $|C|$, $|M|$, $|A|$, $|T|$, $|S|$, $|F|$ and $|P|$, respectively. The number of decision variables in our LR-based algorithm is $|C| \times |M| \times \{1 + |A| \times [3 + |F| + |T| \times (2 + |S|)]\} + |T| \times |S| + |F|$. The required number of total

Lagrangean multipliers is $|C|\times|M|\times\{|A|\times[|T|\times(|F|+2)+|F|+2]+|F|\}+|T|$. In our test network, the problem size is $|C|=10, |M|=92, |A|=3, |F|=60, |T|=10, |S|=3$. Therefore, we can pre-calculate the total number of decision variables is 312,809 and the total number of Lagrangean multipliers is 1,937,530.

Table 5.4: Experiment results for 10 MTs and 10 candidate BSs

$\|C\|$	$\|T\|$	M	K_t	λ_t	Lower Bound	Gap	*PA*	*LR*	Improve	#BSs	#Chs	Time
10	10	1	1	3	1.6535e+007	57.25%	2.7600e+007	2.6000e+007	6.15%	3	42	1
10	10	1	2	3	2.9078e+007	40.31%	4.7200e+007	4.0800e+007	15.69%	6	40	2
10	10	1	3	3	3.8268e+007	43.20%	6.3400e+007	5.4800e+007	15.69%	9	36	29
10	10	2	1	3	1.6784e+007	52.53%	2.7600e+007	2.5600e+007	7.81%	3	39	8
10	10	2	2	3	2.7141e+007	42.22%	4.7200e+007	3.8600e+007	22.28%	6	30	10
10	10	2	3	3	3.3600e+007	41.67%	6.2000e+007	4.7600e+007	30.25%	7	48	27
10	10	3	1	3	1.6935e+007	51.17%	2.7600e+007	2.5600e+007	7.81%	3	39	26
10	10	3	2	3	2.7436e+007	37.05%	4.7200e+007	3.7600e+007	25.53%	5	50	32
10	10	3	3	3	3.3912e+007	33.88%	6.2000e+007	4.5400e+007	36.56%	7	37	86

To measure the time-complexity of the LR-based network-planning algorithm, we attempt to analyze each subproblems of the solution procedure. We denote a polynomial function as $p(n)$. Any algorithm with time-complexity $O(p(n))$ is a polynomial algorithm. In each iteration, the computational complexities of this planning problem are listed in Table 5.5, Table 5.6 and Table 5.7.

All the experiments are performed on a PC with one Pentium IV 2.0 GHz CPU and 1.0 GB DRAM. The operating system running in this computer is Microsoft Windows 2000 Server. The code is written in C language and is complied by Microsoft Visual C++. We depict the analyses of computing time scalability about the scales of connectivity, sectorization, MTs and BSs in Figure 5.1, 5.2, 5.3 and 5.4 respectively.

5.6 Concluding Remarks

The proposed algorithm is the first attempt to consider the network design problem with the whole factors jointly and formulate it rigorously. Due to the time variance and unstable properties of wireless communications, the proposed algorithm is helpful to design high-reliability wireless communication networks. In this chapter, we identify reliability issue of channelized wireless communication networks by introducing customized multiple-connectivity effect. The proposed algorithm not only designs a multiple-connectivity network but also guides to route MT among its candidate homes sequentially. Sequential routing mechanism can combine with FCA to guide real-time admission control to optimize system performance.

We formulate a combinatorial optimization algorithm to deal with this problem. Because this problem is NP-complete, the solution approach we adopt is Lagrangean relaxation. In the computational experiments, we compared the proposed algorithm with the power dominant heuristic on test networks. The proposed algorithm can achieve up to 36.56% improvement of the total cost of network design problems.

Table 5.5: The time-complexity of getting primal feasible solution

Getting primal feasible solution (LR)		
Heuristic	Number of operations required	Time complexity
Heuristic *A*	$\|C\|^2\|M\|\|A\|\|T\|\|S\|\times(\|F\|+\|P\|+1)\times(\|A\|\|T\|\|P\|+\|A\|+1)$	$O(\|C\|^2\|M\|\|A\|^2\|T\|^2\|S\|\|F\|\|P\|)$
Heuristic *B*	$\|T\|\|S\|\times(\|S\|+2\|C\|\|A\|)$	$O(\|C\|\|A\|\|T\|\|S\|)$
Heuristic *C*	$\|C\|\|A\|\|F\|\times(\|T\|+\|F\|+\|C\|\|A\|+\|C\|\|A\|\|F\|\|T\|)$	$O(\|C\|^2\|A\|^2\|F\|^2\|T\|)$

Table 5.6: The time-complexity of Lagrangean relaxation problem

Lagrangean relaxation problem (LR5.1)		
Subproblem	Number of operations required	Time complexity
Initialize	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\times\{\lvert F\rvert+\lvert T\rvert\times(\lvert S\rvert+\lvert F\rvert+\lvert F\rvert^2)\}$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert\lvert F\rvert^2)$
SUB5.1	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert\lvert S\rvert^2\times 30^S$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert\times p(\lvert S\rvert))$
SUB5.2	$\lvert C\rvert\lvert M\rvert\lvert A\rvert$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert)$
SUB5.3	$\lvert C\rvert^2\lvert T\rvert\lvert F\rvert+\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert P\rvert\times\{\lvert F\rvert^2+\lvert F\rvert\lvert T\rvert+\lvert T\rvert^2)\}$	$\max\begin{pmatrix}\lvert C\rvert^2\lvert T\rvert\lvert F\rvert,\\ \lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert P\rvert\lvert F\rvert^2,\\ \lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert P\rvert\lvert T\rvert^2\end{pmatrix}$
SUB5.4	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert F\rvert+\lvert F\rvert+\lvert F\rvert^2$	$\max(O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert F\rvert),O(\lvert F\rvert^2))$

Table 5.7: The time-complexity of Lagrangean dual problem by using the subgradient method

Dual problem (D5.1)		
Multiplier	Number of operations required	Time complexity
μ^1_{tjma}	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert)$
μ^2_{jma}	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert\lvert S\rvert^2$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert\lvert S\rvert^2)$
μ^3_{tijma}	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert\lvert F\rvert^2$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert\lvert F\rvert^2)$
μ^4_{tjma}	$\lvert C\rvert^2\lvert M\rvert\lvert A\rvert\lvert T\rvert\lvert F\rvert$	$O(\lvert C\rvert^2\lvert M\rvert\lvert A\rvert\lvert T\rvert\lvert F\rvert)$
μ^5_{t}	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert T\rvert)$
μ^6_{jma}	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert F\rvert$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert F\rvert)$
μ^7_{ijm}	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert F\rvert$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert F\rvert)$
μ^8_{ijma}	$\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert F\rvert$	$O(\lvert C\rvert\lvert M\rvert\lvert A\rvert\lvert F\rvert)$

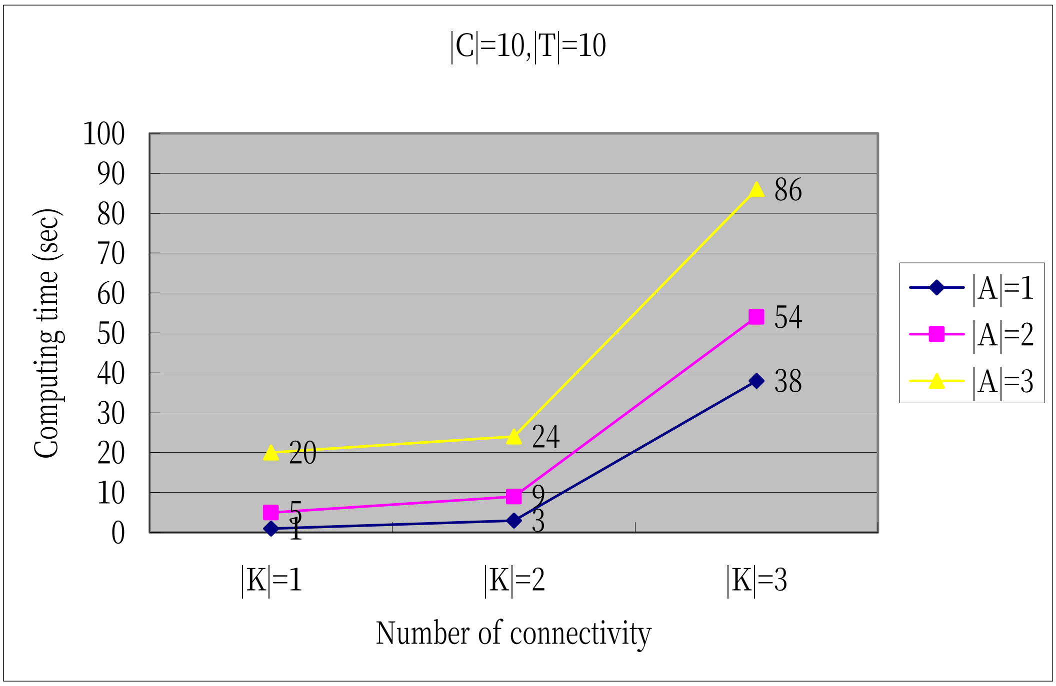

Figure 5.1: The computing time scalability of connectivity

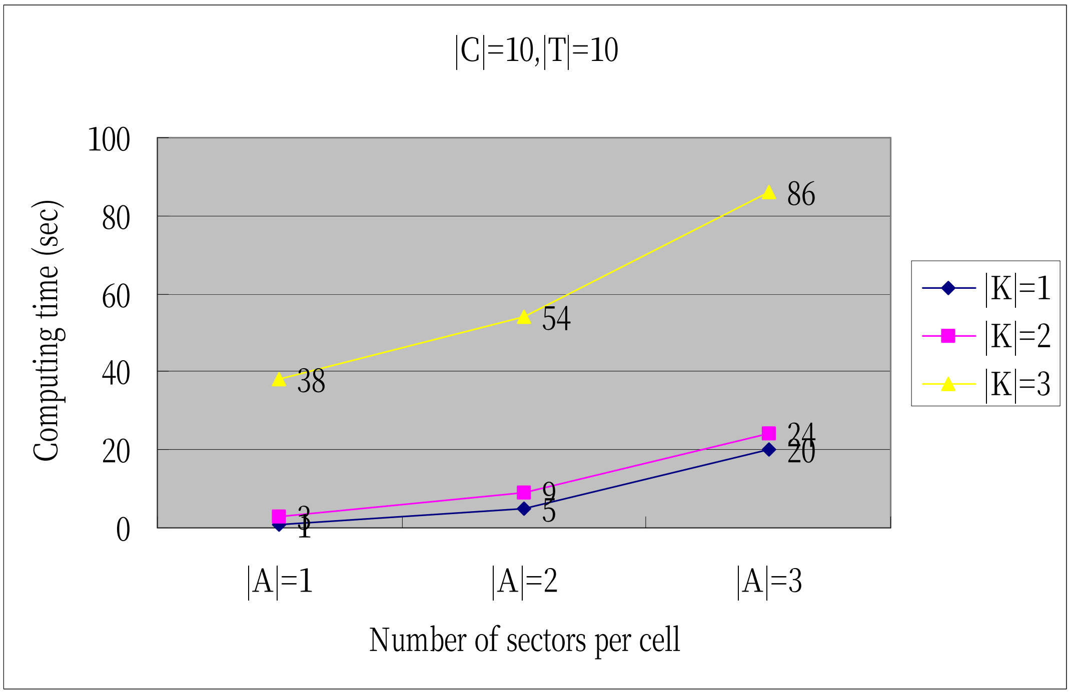

Figure 5.2: The computing time scalability of sectorization

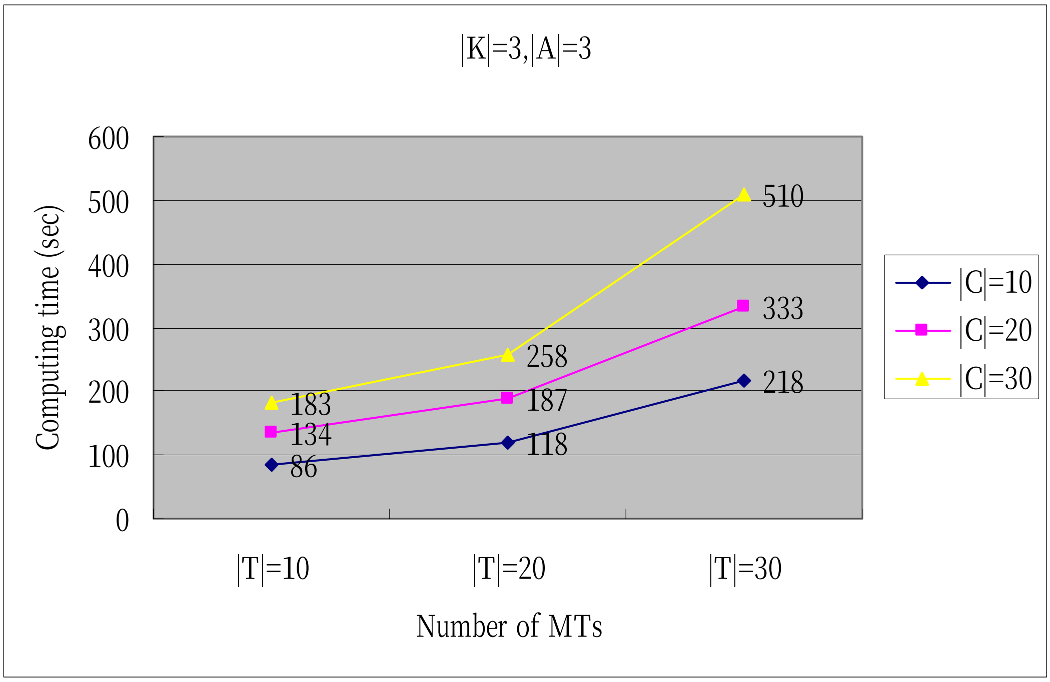

Figure 5.3: The computing time scalability of the number of MTs

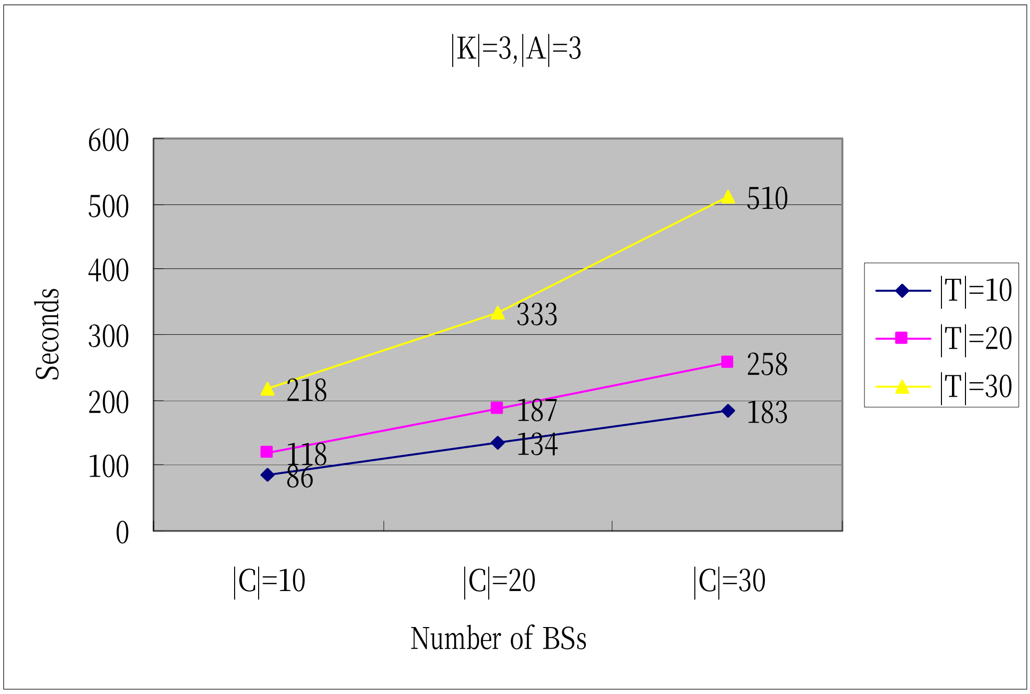

Figure 5.4: The computing time scalability of the number of BSs

6. Performance Assurance and Optimization Module

For an in-service network, performance optimization module handles realtime or quasi-dynamic resource management problems. The objective of performance optimization problems is to optimize a certain performance measure. For wireless communication networks, we can apply admission control, channel assignment and homing policy to optimize our target performance measure.

Call admission control must guarantee both the GoS requirements, i.e., probability of call blocking and call dropping, and the QoS requirement, i.e., CIR constraint. Thus, how to appropriately design call admission control policy and combine with resource allocation mechanism to ensure that performance measure is crucial in wireless communication networks.

In this chapter, we consider the problem of realtime distributed admission controls, FCA and a centralized static sequential homing policy for channelized wireless communication networks. To maximize spectrum efficiency, we study the effect of adjustable channel separation together considering generic channel interference on different propagation environments. For maximizing system revenue purpose, sequential homing policies can cooperate with channel assignment to prearrange channel resource with more efficiency.

The emphasis of this work is to develop a centralized sequential homing and FCA algorithm to support realtime distributed admission control. We formulate the performance optimization problem as a combinatorial optimization problem, where the objective function is to minimize the total call-blocking rate of systems. The solution approach is Lagrangean relaxation. In the computational experiments, we compared the proposed algorithm with the power dominant heuristic on test networks. The proposed algorithm achieved up to 99.9% improvement of the total call-blocking rate.

6.1 Introduction

The demand of real-time network services has been rising fast in many applications. To meet this demand, researchers proposed the concept of a “real-time channel,” that is one of the most notable solutions to the problem of meeting the communication GoS requirements. Generally, two distinct phases are required to realize the concept of real-time channel: off-line channel establishment and run-time message scheduling [80]. The channel establishment phase is of prime importance to the realization of a real-time channel, and during this phase, the system has to select a home for each mobile and allocate sufficient resources to meet the user-specified GoS requirements.

In channelized cellular systems, a given radio spectrum can be divided into a set of disjoint radio channels. All channels can be used simultaneously while maintaining an acceptable received radio signal. In practice, each channel can generate some interference in the adjacent channels. The ACI must be considered even though the effect of such interference can be reduced by adequate adjacent channel separation. Channel interference caused by channel reuse is the most restraining factor on the overall system capacity in the wireless networks. The main idea behind channel assignment algorithms is to make use of radio propagation characteristics and sectorization in order to minimize the total interferences and hence increase the radio spectrum reuse efficiency [38].

In this chapter, we consider the problem of performance optimization in channelized wireless communication networks under the consideration of adjustable channel separation and generic channel interference. We explore the feasibility of optimizing the frequency spacing between carriers such as the combined effect of distance and NFD ratio to maximize the number of available channels in a given propagation environment [63]. To accommodate different situations of smart antenna deployments, we adopt generic sectorization model to formulate irregular cell location, transmission power and sectorization architectures. Both CCI and ACI are accumulated as total interference to evaluate communication QoS. For maximizing system revenue purpose, sequential homing policies can combine with FCA mechanism to rearrange channel resource more efficiently and support realtime distributed admission control.

We formulate the sequential homing problem as a combinatorial optimization problem, where the objective function is to minimize total blocking rate of systems subject to configuration, sequential homing and QoS constraints. The configuration constraints require the assigned channels to be admissible for each sector. Whereas, the QoS constraints require that the call-blocking probability constraint for each sector and CIR constraint received by each MT be satisfied. The basic approach to the algorithm development is Lagrangean relaxation, which has been successfully adopted to solve many famous NP-complete problems [24]. In the computational experiments, the proposed algorithm is shown to be efficient and effective.

The rest of this chapter is organized as follows. Section 6.2 provides the problem description, the notation definitions and problem formulation. In Section 6.3, we adopt Lagrangean relaxation as our solution approach to deal with this problem. In Section 6.4, a primal heuristic and several computational experiment results are presented. Finally, we conclude this problem in Section 6.5.

6.2 Performance Optimization Problem

In order to use the network resources efficiently, bandwidth reservations are made to ensure high probability of calls connection. Traditionally, this task is done in two steps. First, a home must be selected, then, it is set-up and the resources are reserved on its home. However, a home that was computed in the first step may lack the required resources in the second step. Combining the two steps was suggested to overcome this difficulty [11].

Admission control is the acceptance or blocking of call requests. At the cell level, flow enforcement polices a source to ensure that its blocking probability does not exceed the negotiated limit [57][61]. Admission control combined with flow enforcement (policing) can support preventive congestion control mechanism to maximize system revenue subject to the QoS constraint for each MT [59].

6.2.1 Problem Description

As we know, channel assignment schemes can be divided into two kinds: FCA and DCA. In general, there is a trade-off between QoS, the implementation complexity of the channel assignment algorithms and spectrum utilization efficiency. DCA strategies are less efficient than FCA under high load conditions but provide flexibility and traffic adaptability [34].

In this section, realtime distributed admission control does not combine with DCA but with sequential homing based FCA mechanism. We propose a static performance optimization algorithm to determine homing sequences and FCA of total system to achieve the efficiency of channel resources. Whenever we determine the homing sequence for each MT, admission control is a table-lookup procedure and inspects the QoS feasibility of candidate homes sequentially. These admittance computations are avoided at intermediate nodes to support distributed and realtime characteristics.

We depict the notations of the given parameters and decision variables in Table 6.1 and Table 6.2. The system descriptions are listed in the following.

(1) Architectures of wireless communication networks: carrier frequency, available bandwidth and channel separation;

(2) Configurations of BSs: location, antenna height above local terrain height, smart antenna structures, transmission power and maximum channel configuration constraint for each BS;

(3) Characteristics of MTs: antenna heights, receiver sensitivity, candidate set of homing sectors and mean arrival rate of new traffic for each MT.

For each MT, we use Erlang-B formula to model telephony communication networks as an M/G/m/m queueing system under the assumptions that overflow traffic also behaves as Poisson arrival process and average traffic load is used to estimate realtime traffic load.

Table 6.1: Notation descriptions for given parameters.

Given Parameters	
Notation	**Description**
A	the set of sectors in the system
$E(n_j, g_j)$	blocking probability function of Sector j which is a function of traffic demand g_j and available channels n_j.
F	the set of available channels
R_{tj}	received power level of MT $t \in T$ from the downlink signal of Sector $j \in A$
S	the set of permutation which is integer value
T	the set of MTs
$\overline{g_j}$	upper bound of aggregate traffic for Sector j

k_{tj}	indicator function which is 1 if Sector j is one candidate home sector of t and 0 otherwise
$\overline{n}_j$	upper bound of assigned channels for Sector $j \in A$
γ	threshold of acceptable CIR
λ_t	the mean arrival rate of new traffic for each MT $t \in T$
$\theta(\Delta i)$	NFD ratio which is formed as a function of the channel separation (kHz) normalized to the bit-rate (bps)

Table 6.2: Notation descriptions for decision variables

Decision Variables	
Notation	**Description**
B_{ts}	call-blocking probability for the sth candidate homing policy for t which belongs to discrete set $B_{ts} \in K_{ts} = \{0, 0.01, 0.02, ..., \overline{B}_{ts}\}$
b_{tj}	blocking probability of Sector j which is referenced by MT $t \in T$
g_j	aggregate flow on Sector $j \in A$ (in Erlang)
x_{tjs}	homing variable which is 1 if Sector j is selected as the sth homing sequence of MT $t \in T$ and 0 otherwise
y_{ij}	channel assignment decision variable which is 1 if Channel $i \in F$ is assigned to Sector $j \in A$ and 0 otherwise

6.2.2 Problem Formulation

We formulate the problem as an integer-programming problem where the objective function is to minimize the total call-blocking rate of system subject to single home constraints, sequential homing constraints, QoS constraints and configuration constraints.

Objective function (IP6.1) [50]:

$$Z_{IP} = \min \sum_{t \in T} \left(\lambda_t \prod_{s \in S} B_{ts} \right) \quad \text{(IP6.1)}$$

subject to:

$$\sum_{j \in A} x_{tjs} b_{tj} = B_{ts} \qquad \forall t \in T, s \in S \quad (6.1)$$

$$E(\sum_{i \in F} y_{ij}, g_j) = b_{tj} \qquad \forall t \in T, j \in A \quad (6.2)$$

$$\sum_{t \in T} \lambda_t \sum_{s \in S} \left(x_{tjs} \prod_{k=1}^{s-1} B_{tk} \right) = g_j \qquad \forall j \in A \quad (6.3)$$

$$k_{tj} \sum_{j' \in A} \sum_{i' \in F} \frac{R_{tj'}}{R_{tj}} y_{i'j'} \theta(|i - i'|) \le G_j + (\frac{1}{\gamma} + 1 - G_j) y_{ij} \qquad \forall i \in F, j \in A, t \in T \quad (6.4)$$

$$\sum_{i \in F} y_{ij} \le \bar{n}_j \qquad \forall j \in A \quad (6.5)$$

$$\sum_{j \in A} x_{tjs} = 1 \qquad \forall t \in T, s \in S \quad (6.6)$$

$$\sum_{s \in S} x_{tjs} \le k_{tj} \qquad \forall t \in T, j \in A \quad (6.7)$$

$$x_{tjs} = 0 \text{ or } 1 \qquad \forall t \in T, j \in A, s \in S \quad (6.8)$$

$$y_{ij} = 0 \text{ or } 1 \qquad \forall j \in A, i \in F \quad (6.9)$$

$$0 \le B_{ts} \le \bar{B}_{ts} \qquad \forall t \in T, s \in S, B_{ts} \in K_{ts} \quad (6.10)$$

$$0 \le b_{tj} \le \bar{b}_{tj} \qquad \forall t \in T, j \in A \quad (6.11)$$

$$0 \le g_j \le \bar{g}_j \qquad \forall j \in A. \quad (6.12)$$

The objective is to minimize the call-blocking rate of total system. Constraint (6.1) is the call-blocking probability of MT t on the permutation *s*. Constraint (6.2) decomposes the call-blocking probability of Sector j by introducing one additional notation b_{tj}. Constraint (6.3) calculates the aggregate traffic for Sector j. Constraint (6.4) ensure CIR requirement for MTs, which are homed to Sector j. Constraint (6.5) enforces configuration constraint for Sector j. Constraint (6.6) enforces that only one candidate homed BS can be selected for each MT t on each permutation *s*. Constraint (6.7) enforces that the number of candidate path is equal to the number of homing decisions. Constraints (6.8) and (6.9) enforce the integer property of the decision variables x_{tjs} and y_{ij}. Constraint (6.10) limits the feasible discrete region of path blocking probability. Constraints (6.11) and (6.12) enforce the feasible regions of call-blocking probability and aggregate traffic for each sector.

6.3 Solution Procedure

The performance optimization problem is an integer-programming problem with highly non-convexity form. In general, this problem is NP-complete [27]. The following lemma specifies the deduction of NP-complete property.

Lemma 6.1: this kind of performance optimization problems is NP-complete

Proof:

By adopting problem reduction technique of NP-completeness, the performance optimization problem (IP6.1) can be reduced as a generalized channel assignment problem by fixing all decision variables except channel assignment variable y_{ij} as given parameters. As we know that a generalized graph-coloring problem is proved a NP-complete problem [27], the problem (IP6.1) is one kind of generalized graph-coloring problems. The performance optimization problem is more complex than the problem (IP6.1). That is, the kind of performance optimization problems is NP-complete.□

Because the above fixed sequential homing problem is NP-complete, we do not expect to develop an optimal algorithm for large-scale problems. Instead, an efficient Lagrangean-based algorithm is developed.

6.3.1 Lagrangean Relaxation Method

By using Lagrangean relaxation, we relax three complicate constraints. Two of them are integer programming problems, which are Constraints (6.2) and (6.4) and another one is signomial problem, that is Constraint (6.3). These constraints must be multiplied by Lagrangean multipliers and added to the objective function. After dualizing these complicating constraints, we can construct the following Lagrangean relaxation problem.

Objective function:

$$Z_{LR1}(\mu_{tj}^1, \mu_j^2, \mu_{jit}^3) = \min \sum_{t\in T}\left(\lambda_t \prod_{s\in S} B_{ts} \right) + \sum_{t\in T}\sum_{j\in A} \mu_{tj}^1 \left(E(\sum_{i\in F} y_{ij}, g_j) - b_{tj} \right)$$

$$+ \sum_{j\in A}\sum_{i\in F}\sum_{t\in T} \mu_{jit}^3 \left(k_{tj} \sum_{j'\in A}\sum_{i'\in F}\left(\frac{R_{tj'}}{R_{tj}} y_{i'j'} \theta(|i-i'|) \right) - G_j - (\frac{1}{\gamma} + 1 - G_j) y_{ij} \right)$$

$$+ \sum_{j\in A} \mu_j^2 \left(\sum_{t\in T} \lambda_t \sum_{s\in S}\left(x_{tjs} \prod_{k=1}^{s-1} B_{tk} \right) - g_j \right) \quad \text{(LR6.1)}$$

subject to: (6.1), (6.5), (6.6), (6.7), (6.8), (6.9), (6.10), (6.11) and (6.12).

In this formulation, all $\mu_{tj}^1, \mu_j^2, \mu_{jit}^3$ are Lagrange multipliers but only μ_{jit}^3 must be positive. To solve this problem, we can decompose (LR6.1) into the following two independent and solvable optimization subproblems.

Subproblem 6.1: (related with decision variables B_{ts}, x_{tjs} and b_{tj})

Objective function:

$$Z_{SUB1} = \min \sum_{t\in T}\left(\lambda_t \prod_{s\in S} B_{ts} \right) - \sum_{t\in T}\sum_{j\in A} \mu_{tj}^1 b_{tj} + \sum_{t\in T}\sum_{j\in A}\sum_{s\in S}\left(\mu_j^2 \lambda_t x_{tjs} \prod_{k=1}^{s-1} B_{tk} \right) \quad \text{(SUB6.1)}$$

subject to: (6.1), (6.6), (6.7), (6.8), (6.10) and (6.11).

We can decompose this problem into $|T|$ subproblems. Each subproblem solves the following problem.

$$Z_{SUB1_t} = \min \lambda_t \prod_{s\in S} B_{ts} - \sum_{j\in A} \mu_{tj}^1 b_{tj} + \sum_{j\in A}\sum_{s\in S}\left(\mu_j^2 \lambda_t x_{tjs} \prod_{k=1}^{s-1} B_{tk} \right) \qquad \forall t \in T \text{ (SUB6.1}t)$$

As the property of decision variable x_{tjs} and given parameter k_{tj}, we can exhaustively search for all possible combination value of $x_{tjs} \times k_{tj}$ to calculate minimum objective value for subproblem 6.1.

Subproblem 6.2: (related with decision variables y_{ij} and g_j)

$$Z_{SUB2} = \min \sum_{t\in T}\sum_{j\in A}\mu_{tj}^{1}E(\sum_{i\in F}y_{ij}, g_j) - \sum_{j\in A}\mu_j^2 g_j$$

$$+\sum_{j\in A}\sum_{i\in F}\sum_{t\in T}\mu_{jit}^{3}\left(k_{tj}\sum_{j'\in A}\sum_{i'\in F}\frac{R_{tj'}}{R_{tj}}y_{i'j'}\theta(|i-i'|) - G_j - (\frac{1}{\gamma}+1-G_j)y_{ij}\right) \qquad \text{(SUB6.2)}$$

subject to: (6.5), (6.9) and (6.12).

We can decompose this problem into |*A*| subproblems. Each subproblem solves the following problem (SUB6.2*a*):

$$Z_{SUB2_c} = \min \sum_{t\in T}\mu_{tj}^{1}E(\sum_{i\in F}y_{ij}, g_j) - \mu_j^2 g_j - \sum_{i\in F}\sum_{t\in T}\mu_{jit}^{3}G_j$$

$$+\sum_{i\in F}y_{ij}\sum_{t\in T}\left(\sum_{j'\in A}\sum_{i'\in F}\frac{R_{tj}}{R_{tj'}}k_{tj'}\mu_{j'i't}^{3}\theta(|i'-i|) - \mu_{jit}^{3}(\frac{1}{\gamma}+1-G_j)\right) \qquad \forall j\in A.$$

6.3.2 The Dual Problem and the Subgradient Method

According to the weak Lagrangean duality theorem, for any $\mu_{jit}^3 \ge 0$ and μ_{tj}^1, μ_j^2, the objective value of $Z_{LR1}(\mu_{tj}^1, \mu_j^2, \mu_{jit}^3)$ is a lower bound of Z_{IP} [15]. The following dual problem (D6.1) is then constructed to calculate the tightest lower bound.

$$Z_D = \max_{\mu_{jit}^3 \ge 0} Z_{LR1}(\mu_{tj}^1, \mu_j^2, \mu_{jit}^3). \qquad \text{(D6.1)}$$

We use the subgradient method to solve the dual problem (D6.1). In this dual problem, let a vector χ be a subgradient of problem $Z_{LR1}(\mu_{tj}^1, \mu_j^2, \mu_{jit}^3)$. In iteration k of the subgradient optimization procedure, the multiplier vector π is updated by π^{k+1} =

$\pi^k + \xi^k \chi^k$. The step size ξ^k is determined by $\xi^k = \varsigma \frac{Z_{IP1}^h - Z_{D1}(\pi_k)}{\left\| \chi^k \right\|^2}$, where Z_{IP}^h is the primal objective function value for a heuristic [25][30]. It is an upper bound on Z_{IP}.

6.3.3 Getting Primal Feasible Solutions

When we use Lagrangean relaxation method as our solution approach to solve the problems, we not only get a theoretical lower bound of primal feasible solutions, but also get some hints in the process of solving dual problem iteratively. More precisely, when solving the dual problem iteratively, a Lagrangean relaxation problem is solved. If the decision variables are feasible and satisfy all of the constraints in the primal problem, then a primal feasible solution is found. Otherwise, modification on such infeasible primal solutions can be made to obtain primal feasible solutions. In order to get primal feasible solutions, we propose a homing dominant primal algorithm, denoted by Algorithm *A*. In Algorithm *A*, we use the permutation results as the dominant decision and then allocate available channels by load-balance approach.

- **Algorithm *A***

Step 1. Initialize permutation *s*=0 to denote the first homing situation for all MTs.

Step 2. For each sector j, apply the sequential homing policy, referred to the results of x_{hs} from Lagrangean dual problem, to pre-calculate the aggregate traffic under permutation *s* situation by Constraint (6.3).

Step 3. For channel assignment purpose, we calculate the blocking rate reduction level for each sector j and then sort sector order by their contribution of reducing objective value if assigning one additional channel to sector.

Step 4. Use the hints from Lagrangean dual problem to sort channel order for Sector *j*. The coefficient of channel assignment decision variables y_{ij} is defined as

$$\text{Coef}\left(y_{ij}\right)=\sum_{t\in T}\left(k_{tj}\sum_{j'\in A}\sum_{i'\in F}\frac{R_{tj}}{R_{tj'}}\mu^{3}_{j'i't}\delta_{hj'}\theta(|i'-i|)-\mu^{3}_{jit}(\frac{1}{\gamma}+1-G_{j})\right).$$

Step 5. Assign the lowest coefficient channel *i* to the greatest objective reduction sector *j* and then check the feasibility of this assignment. We must ensure the configuration constraints for Sector *j* (Constraint (6.5)) and the QoS constraints for each MT that is homed to Sector *j* (Constraint (6.4)).

Step 6. If the QoS constraints are feasible, assign this Channel *i* to Sector *j*, change the system status, resort sector order and then go to Step 3. Otherwise, retry to assign next channel for Sector *j* by go to Step 5. If the configuration constraints or blocking probability constraints violate, go to Step 7 to apply drop-and-add approach to modify sequential homing policy.

Step 7. For tuning infeasible solution purpose, we sort all sectors by its residue capacity in descending order to construct modify sector order. This sector order reveals the sector modifiability to reroute more traffic from infeasible sectors.

Step 8. Reroute the traffic load of multiple candidate-home MT from the most infeasible sector to the greatest modifiability sector. Check the feasibility of both modified sectors and modify the sequential homing decision.

Step 9. If the most infeasible sector is still infeasible, go to Step 8 to reroute more traffic. If there is any sector still infeasible, go to Step 7 for further tuning.

Step 10. If all permutations have been processed, calculate the objective value and keep the best feasible solution. Otherwise, set s=s+1 and go to Step 2 for processing next permutation phase.

6.4 Computational Experiments

In this section, we randomly generate a sectorization wireless network topology as our experiment environment. In this topology, there are 5 BSs constructed by 15 smart antennas to service 20 MT clusters under the GSM-like situation that frequency is on 900 MHz, bandwidth is 12.5 MHz, CIR is 9 dB, average MT height is between 1 m to 10 m, average BS height is between 30 m to 200 m. For comparison purpose, we also develop a primal heuristic as follows.

6.4.1 Primal Heuristic

To develop a primal heuristic, we adopt the most traditional homing policy, which homes each MT prioritizing to the greatest received downlink power sector, and denote as Heuristic *H*. In Heuristic *H*, the homing permutation is in descending order of received power. The sector order for assigning channel is the same with Algorithm *A* by sorting the contribution of reducing objective value in descending order. For simplicity purpose, we assign channel just by the order of channel identifiers. The detail description of this primal heuristic is described in the following.

- **Heuristic *H***

Step 1. For each MT, follow received power dominant rule to become the homing sequence of each MT. Initialize s=0 and begin to process the first homing phase.

Step 2. For each sector, calculate the aggregate traffic on each permutation situation s.

Step 3. Sort sectors in descending order of their blocking rate reduction.

Step 4. Using the channel identifier as the channel order, check sequentially the feasibility of channel assignment policy for the greatest objective reduction sector j.

Step 5. If the QoS constraints are feasible, assign this Channel *i* to Sector *j*, change the system status, resort sector order and then go to Step 3. Otherwise, retry to assign the next channel for Sector *j* by going to Step 4. If the configuration constraints or blocking probability constraints are violated, re-home the MT to the next candidate home sector.

Step 6. If all permutation cases have been processed, calculate the objective value and keep the best feasible solution. Otherwise, set $s=s+1$ and go to Step 2 for processing the next permutation phase.

6.4.2 Experiment Results

After several computational experiments, we list all of the experiment results together in Table 6.3. To explore the effect of adjustable channel separation, the experiments perform the network on different propagation environment to evaluate the effect of adjustable channel separation. In these cases, we can find that different propagation environments have different niche channel separation. In this GSM-like test environment, the performance of 100 kHz channel separation is better than that of the standard GSM system, whose channel separation is 200 kHz.

In the second experiment, we compare the computational results of Algorithm *A* and Heuristic *H* to evaluate the efficiency and effectiveness of the proposed algorithm. In these experiments, we can observe that as the traffic load increases, Algorithm *A* can achieve a feasible solution but Heuristic *H* cannot. Furthermore, Algorithm *A* achieved up to 99% improvement of the total call-blocking rate from Heuristic *H*.

Table 6.3: Experiment results of Algorithm *A* and Heuristic *H*.

Case	Areas	Δi	λ_t	Algorithm *A*	Heuristic *H*	Improvement
1	open	50	2	8.4781 e-10	1.1600 e-04	99.9%
2	open	100	2	5.8552 e-19	8.2101 e-04	100%
3	open	200	2	2.6054 e-13	1.0501 e-02	100%
4	open	300	2	2.6515 e-04	1.7376 e-01	99.8%
5	open	50	5	6.6102 e-03	9.0580 e-01	99.2%
6	open	100	5	3.2364 e-09	9.6843 e-01	99.9%
7	open	200	5	2.0477 e-03	3.0707 e+00	99.9%
8	open	300	5	5.0930 e+00	N/A	---
9	open	100	10	1.7254 e-07	N/A	---
10	open	200	10	5.4591 e+00	N/A	---
11	open	300	10	N/A	N/A	---
12	urban	50	2	1.1209 e-13	9.9436 e-05	100%
13	urban	100	2	7.0688 e-26	2.5741 e-04	100%
14	urban	200	2	7.6380 e-05	2.5839 e-02	99.7%
15	urban	300	2	3.8196 e-04	6.3651 e-01	99.9%
16	urban	50	5	1.6912 e-02	2.9121 e+00	99%
17	urban	100	5	3.5969 e-06	2.9843 e+00	99.9%
18	urban	200	5	9.7828 e-01	N/A	---
19	urban	300	5	1.5764 e+01	N/A	---

6.5 Concluding Remarks

In this chapter, we consider the problem of performance optimization for channelized wireless communication networks. Instead of adopting DCA policy, we develop a FCA model to combine with centralized sequential homing mechanism to support realtime admission control, channel assignment and homing issues to maximize average system performance. Furthermore, we study the effect of adjustable channel separation together considering generic channel interference on different propagation environments.

We formulate the performance optimization problem as a combinatorial optimization problem and use Lagrangean relaxation as our solution approach. In the computational experiments, the proposed channel separation is better than GSM system. We also compared the proposed algorithm with the power dominant heuristic on test networks. The proposed algorithm achieved on average up to 99.9% improvement of the total call-blocking rate.

7. Network Servicing Module

Using corrective actions to alleviate the performance exceptions is the major objective of network-servicing module [55]. In wireless communication networks, channel reassignment, augmentation, configuration re-arrangement and re-homing mechanisms are the major treatments of wireless network servicing problems.

In this chapter, we study the problem of channel reassignment, augmentation, homing and transmission power control in wireless communication networks under the consideration of irregular BS allocation/sectorization and generic channel interference, including both CCI and ACI. Channel reassignment may be required in a wireless communication network when channel interference and/or the distribution of traffic demand changes. Like channel reassignment, sector transmission power control is another effective and economical measure to alleviate performance problems. However, when the traffic demand exceeds a critical point and the current network capacity becomes insufficient, channel augmentation is required despite the application of the above-mentioned two cost-effective measures. We formulate this problem as a combinatorial optimization problem, where the objective function is to minimize the channel augmentation cost subject to configuration, capacity, QoS and GoS constraints. The basic approach to the algorithm development is Lagrangean relaxation. In computational experiments, the proposed algorithm is shown to be efficient and effective. The proposed algorithm can achieve up to 66.67% improvement of the total channel augmentation fee.

7.1 Introduction

In order to efficiently utilize the scarce spectrum resource in wireless networks, channel assignment is becoming one of the most important issues for wireless communication researchers. Whether the channel sharing is based upon given BS configuration environment, there exists a fundamental limit on the number of users sharing the same frequency simultaneously. Since higher resource utilization can achieve higher service revenue gains, the objective of this chapter is to reorganize original BS configuration by optimizing channel utilization and transmission power control to achieve higher system resource utilization.

In this chapter, we propose a more generic sectorization approach to model any kind of real wireless networks and operate the resource management of real wireless communication systems more precisely. We estimate the frequency interference precisely by accumulating all interference from all of the other sectors to the interested sector. We together accumulate the CCI and ACI in our QoS assurance approach to calculate the total interferences on MTs when resource management policy is applied. By doing that, we can assure that received interference must not violate the CIR constraint.

In general, channel reassignment, augmentation and power control problem on generic sectorization structure is NP-complete and is more complex than traditional channel assignment problem. We formulate the problem as an integer programming problem where the objective function is to minimize the channel augmentation cost subject to configuration, capacity, QoS and GoS constraints.

The rest of this chapter is organized as follows. Section 7.2 develops the problem formulation. Section 7.3 describe the solution procedure and LR-based algorithm. Section 7.4 is our computational experiments. Finally, we conclude this problem in Section 7.5.

7.2 Resource Rearrangement and Augmentation Problem

7.2.1 Problem Description

Channel reassignment, augmentation and power control are corrective actions for wireless networks to alleviate the performance exceptions. In the performance rearrangement and augmentation problem, the objective is to minimize the channel augmentation cost. The decision will be how to reassign existing channels to deal with the changes of channel interference and/or the distribution of traffic demand. Transmission power control and rehoming are also effective and economical measures to alleviate performance problems for each sector [41]. As the traffic demand grows and exceeds a critical performance point, the current network capacity becomes insufficient despite the application of the above-mentioned two cost-effective measures. A channel augmentation decision is required to expand system capacity for network sizing purpose. The given parameters and decision variables for this algorithm to formulate generic network servicing and sizing problem are defined in Table 7.1 and 7.2 respectively.

Table 7.1: Notation descriptions for given parameters

Given Parameters	
Notation	**Description**
A	the set of sectors
$D_{jj'}(r_j)$	minimum distance between interested Sector *j* and interfering Sector *j'* under the condition of the transmission radius of Sector *j*
F	the set of available existing channels

F'	the set of available augmentation channels
G_j	an arbitrarily large number
$Q(g_j, \beta_j)$	minimum number of channels required for traffic demand g_j so that the call-blocking probability shall not exceed β_j
T	the set of MTs
d_{tj}	the distance between Sector *j* and MT *t*
h_{tj}	the original homing relationship between MT *t* and Sector *j*
k_{tj}	indicator function which is 1 if MT *t* locates in the candidate service area of Sector *j* and 0 otherwise
$\bar{n}_j$	upper bound on number of channels that can be assigned to Sector *j*
$\bar{r}_j$	upper bound of transmission radius of Sector *j*
z_{ij}	indicator function which is 1 if existing Channel *i* is used by Sector *j* and 0 otherwise
α_j	attenuation factor (2< α <6) for Sector *j*
β_j	threshold of acceptable call-blocking probability of Sector *j*
γ_j	threshold of acceptable CIR (in dB) of Sector *j*
θ	the NFD ratio is the filter reduction constant for adjacent frequencies
λ_t	traffic load of MT *t*
Δ_F	license fee function of augmentation Channel *i*
Φ_i^F	loss of revenue for the decision of reassignment existing channel *i*
Φ_t^H	loss of revenue for the decision of re-homing MT *t*
Φ_j^A	the loss revenue limitation for Sector *j* to rearrange channel assignment and power level

Table 7.2: Notation descriptions for decision variables

Decision Variables	
Notation	**Description**
f_i	decision variable which is 1 if augmentative channel *i* ($i \in A$) is installed and 0 otherwise
g_j	the aggregate flow on Sector *j*
r_j	decision variable which is the transmission radius of Sector *j*
x_{tj}	decision variable which is 1 if MT *t* is homed to Sector *j* and 0 otherwise
y_{ij}	decision variable which is 1 if Channel *i* is assigned to Sector *j* and 0 otherwise

7.2.2 Problem Formulation

This problem can be formulated as the following integer programming problem.

Objective function (IP7.1):

$$Z_{IP1} = \min \sum_{i \in F'} \Delta_F f_i \qquad \text{(IP7.1)}$$

subject to:

$$\sum_{i \in F} \Phi_i^F \left(y_{ij}(1-2z_{ij}) + z_{ij} \right) + \sum_{t \in T} \Phi_t^H \left(x_{tj}(1-2h_{tj}) + h_{tj} \right) \le \Phi_j^A \qquad \forall j \in A \qquad (7.1)$$

$$\sum_{j' \in A} \theta \times \left(y_{(i-1),j'} + y_{(i+1),j'} \right) \left(\frac{r_{j'}}{D_{jj'}(r_j)} \right)^{\alpha_{j'}} + \sum_{j' \in A-\{j\}} y_{ij'} \left(\frac{r_{j'}}{D_{jj'}(r_j)} \right)^{\alpha_{j'}} \le G_j + \left(\frac{1}{\gamma_j} - G_j\right) y_{ij}$$

$$\forall j \in A, i \in F \cup F' \qquad (7.2)$$

$$Q(g_j, \beta_j) \le \sum_{i \in F \cup F'} y_{ij} \qquad \forall j \in A \qquad (7.3)$$

$$\sum_{t \in T} \lambda_t x_{tj} \le g_j \qquad \forall j \in A \qquad (7.4)$$

$$d_{tj} x_{tj} \le r_j k_{tj} \qquad \forall j \in A, t \in T \qquad (7.5)$$

$$x_{tj} \le k_{tj} \sum_{i \in F \cup F'} y_{ij} \qquad \forall j \in A, t \in T \qquad (7.6)$$

$$y_{ij} \le f_i \qquad \forall j \in A, i \in F' \qquad (7.7)$$

$$\sum_{i \in F \cup F'} y_{ij} \leq \bar{n}_j \qquad \forall j \in A \qquad (7.8)$$

$$\sum_{j \in A} x_{tj} = 1 \qquad \forall t \in T \qquad (7.9)$$

$$0 \leq r_j \leq \bar{r}_j \qquad \forall j \in A \qquad (7.10)$$

$$f_i = 0 \text{ or } 1 \qquad \forall i \in F' \qquad (7.11)$$

$$y_{ij} = 0 \text{ or } 1 \qquad \forall j \in A, i \in F \cup F' \qquad (7.12)$$

$$x_{tj} = 0 \text{ or } 1 \qquad \forall j \in A, t \in T\,. \qquad (7.13)$$

The objective function is to minimize the license fee of augmentation channels. Constraint (7.1) is reformulated for the purpose to ensure that the loss revenue of call dropping due to channel reassignment $\sum_{i \in F} \Phi_i^F \left| y_{ij} - z_{ij} \right|$ and rehoming $\sum_{t \in T} \Phi_t^H \left| x_{tj} - h_{tj} \right|$ is lower than the modification cost constraint. Constraint (7.2) is to ensure that the sum of interferences introduced by other co-channel sectors and near-channel sectors is less than the CIR threshold for each channel. Constraints (7.3) and (7.4) are to ensure that the number of channels assigned to each sector is larger enough than the required minimum trunks to service aggregate traffic. Constraint (7.5) is to ensure that one sector can only serve those MTs that are in its coverage area of effective candidate radius of sector. Constraint (7.6) is to ensure that a sector cannot provide any service if no channel was allocated to it. Constraint (7.7) counts the number of augmentation channels used in this system. Constraint (7.8) is to ensure that the number of channels assigned to each sector satisfies its configuration limitation. Constraint (7.9) is to enforce that one MT can only home to one sector. Constraint (7.10) is to ensure that the transmission radius of each sector ranges is between 0 and the maximum transmission radius limitation. Constraints (7.11), (7.12) and (7.13) enforce the integer property of the decision variables.

7.3 Solution Procedure

Because the above integer programming formulation problem is NP-complete [27], we use Lagrangean relaxation as our solution approach to these problems [24]. In applying the Lagrangean relaxation approach, several complicating constraints are relaxed, i.e. Constraints (7.1) to (7.7). Then, we can transform the primal problem (IP7.1) into the following Lagrangean relaxation problem (LR7.1).

7.3.1 Lagrangean Relaxation Method

For a vector of Lagrangean multipliers, a Lagrangean relaxation problem of (IP7.1) is given by optimization problem.

Lagrangean relaxation problem (LR7.1):

$$
\begin{aligned}
&Z_{LR1}(\mu_j^1,\mu_{ji}^2,\mu_j^3,\mu_j^4,\mu_{jt}^5,\mu_{jt}^6,\mu_{ji}^7) = \min \sum_{i\in F'} \Delta_F f_i \\
&+\sum_{j\in A}\mu_j^1\left(\sum_{i\in F}\Phi_i^F\left(y_{ij}(1-2z_{ij})+z_{ij}\right)+\sum_{t\in T}\Phi_t^H\left(x_{tj}(1-2h_{tj})+h_{tj}\right)-\Phi_j^A\right) \\
&+\sum_{j\in A}\sum_{i\in F\cup F'}\mu_{ji}^2\left(\begin{array}{l}\sum_{j'\in A}\theta\times\left(y_{(i-1),j'}+y_{(i+1),j'}\right)\left(\dfrac{r_{j'}}{D_{jj'}(r_j)}\right)^{\alpha_{j'}}+\sum_{j'\in A-\{j\}}y_{ij'}\left(\dfrac{r_{j'}}{D_{jj'}(r_j)}\right)^{\alpha_{j'}} \\ -\left(G_j+(\dfrac{1}{\gamma_j}-G_j)y_{ij}\right)\end{array}\right) \\
&+\sum_{j\in A}\mu_j^3\left(Q(g_j,\beta_j)-\sum_{i\in F\cup F'}y_{ij}\right)+\sum_{j\in A}\mu_j^4\left(\sum_{t\in T}\lambda_t x_{tj}-g_j\right)+\sum_{j\in A}\sum_{t\in T}\mu_{jt}^5\left(d_{tj}x_{tj}-r_jk_{tj}\right) \\
&+\sum_{j\in A}\sum_{t\in T}\mu_{jt}^6\left(x_{tj}-k_{tj}\sum_{i\in F\cup F'}y_{ij}\right)+\sum_{j\in A}\sum_{i\in F'}\mu_{ji}^7\left(y_{ij}-f_i\right) \qquad \text{(LR7.1)}
\end{aligned}
$$

subject to: (7.8), (7.9), (7.10), (7.11), (7.12) and (7.13).

In this formulation, $\mu_j^1, \mu_{ji}^2, \mu_j^3, \mu_j^4, \mu_{jt}^5, \mu_{jt}^6, \mu_{ji}^7$ are Lagrange multipliers and all of them are non-negative integers. The problem can be decomposed into four independent sub-problems.

Subproblem (SUB7.1): (related with decision variables y_{ij} and r_j)

$$Z_{SUB1} = \min \sum_{j\in A}\sum_{i\in F\cup F'} y_{ij}\left(\mu_{ji}^2 (G_j - \frac{1}{\gamma_j}) + \sum_{j'\in A}\left(\mu_{j',(i-1)}^2\theta + \mu_{j'i}^2 + \mu_{j',(i+1)}^2\theta\right)\left(\frac{r_j}{D_{j'j}(r_{j'})}\right)^{\alpha_j} \right)$$
$$+ \sum_{j\in A}\left(\sum_{i\in F}\mu_j^1 \Phi_i^F (1-2z_{ij}) y_{ij} + \sum_{i\in F'}\mu_{ji}^7 y_{ij} - \sum_{i\in F\cup F'} y_{ij}\left(\mu_j^3 + \sum_{t\in T}\mu_{jt}^6 k_{tj}\right)\right)$$
$$+ \sum_{j\in A}\left(\sum_{j'\in A}\theta\left(\mu_{j'1}^2 y_{0j} + \mu_{j'n}^2 y_{(n+1),j}\right)\left(\frac{r_j}{D_{j'j}(r_{j'})}\right)^{\alpha_j} - \sum_{i\in F\cup F'}\mu_{ji}^2 y_{ij}\left(\frac{r_j}{D_{jj}(r_j)}\right)^{\alpha_j} - \sum_{t\in T}\mu_{jt}^5 k_{tj} r_j \right) \tag{SUB7.1}$$

subject to: (7.8), (7.10) and (7.12).

Because the transmission radius r_j for each sector belongs to a limited discrete set, we can decompose this subproblem into $|A|$ subproblems and exhaustively search each radius case with the following formulation.

$$Z_{SUB1a} = \min \sum_{i\in F} y_{ij}\left(\mu_{ji}^2 (G_j - \frac{1}{\gamma_j}) + \sum_{j'\in A}\left(\mu_{j',(i-1)}^2\theta + \mu_{j'i}^2 + \mu_{j',(i+1)}^2\theta\right)\left(\frac{r_j}{D_{j'j}(r_{j'})}\right)^{\alpha_j} \right)$$
$$+ \sum_{i\in F} y_{ij}\left(\mu_j^1 \Phi_i^F (1-2z_{ij}) - \mu_j^3 - \sum_{t\in T}\mu_{jt}^6 k_{tj}\right) + \sum_{i\in F'} y_{ij}\left(\mu_{ji}^7 - \mu_j^3 - \sum_{t\in T}\mu_{jt}^6 k_{tj}\right)$$
$$+ \sum_{i\in F'} y_{ij}\left(\mu_{ji}^2 (G_j - \frac{1}{\gamma_j}) + \sum_{j'\in A}\left(\mu_{j',(i-1)}^2\theta + \mu_{j'i}^2 + \mu_{j',(i+1)}^2\theta\right)\left(\frac{r_j}{D_{j'j}(r_{j'})}\right)^{\alpha_j} \right)$$
$$+ \sum_{j'\in A}\theta\times\left(\mu_{j'1}^2 y_{0j} + \mu_{j'n}^2 y_{(n+1),j}\right)\left(\frac{r_j}{D_{j'j}(r_{j'})}\right)^{\alpha_j} - \sum_{i\in F\cup F'}\mu_{ji}^2 y_{ij}\left(\frac{r_j}{D_{jj}(r_j)}\right)^{\alpha_j} - \sum_{t\in T}\mu_{jt}^5 k_{tj} r_j \tag{SUB7.1a}$$

To solve (SUB7.1*a*), we can determine decision variables by divide-and-conquer approach. We separately determine the channel assignment problem for existing channels $i \in F$ and the channel augmentation problem for augmentative channels $i \in F'$ by the following two sub-problems.

- For each existing channel $i \in F$:

$$Z_{SUB1af} = \min \sum_{i \in F} y_{ij} \left(\mu_{ji}^2 (G_j - \frac{1}{\gamma_j}) + \sum_{j' \in A} \left(\mu_{j',(i-1)}^2 \theta + \mu_{j'i}^2 + \mu_{j',(i+1)}^2 \theta \right) \left(\frac{r_j}{D_{j'j}(r_{j'})} \right)^{\alpha_j} + \mu_j^1 \Phi_i^F (1 - 2z_{ij}) - \mu_j^3 - \sum_{t \in T} \mu_{jt}^6 k_{tj} \right) \quad \text{(SUB7.1}af\text{)}$$

subject to: (7.10) and (7.12).

- For each augmentation channel $i \in F'$:

$$Z_{SUB1af'} = \min \sum_{i \in F'} y_{ij} \left(\mu_{ji}^2 (G_j - \frac{1}{\gamma_j}) + \sum_{j' \in C} \left(\mu_{j',(i-1)}^2 \theta + \mu_{j'i}^2 + \mu_{j',(i+1)}^2 \theta \right) \left(\frac{r_j}{D_{j'j}(r_{j'})} \right)^{\alpha_j} + \mu_{ji}^7 - \mu_j^3 - \sum_{t \in T} \mu_{jt}^6 k_{tj} \right) \quad \text{(SUB7.1}af'\text{)}$$

subject to: (7.10) and (7.12).

Therefore, the original objective value of problem (SUB7.1) can be minimized after solving (SUB7.1*af*) and(SUB7.1*af'*):

$$Z_{SUB1a} = \min Z_{SUB1af} + Z_{SUB1af'} + \sum_{j' \in A} \theta \left(\mu_{j'1}^2 y_{0j} + \mu_{j'n}^2 y_{(n+1),j} \right) \left(\frac{r_j}{D_{j'j}(r_{j'})} \right)^{\alpha_j} - \sum_{i \in F \cup F'} \mu_{ji}^2 y_{ij} \left(\frac{r_j}{D_{jj}(r_j)} \right)^{\alpha_j} - \sum_{t \in T} \mu_{jt}^5 k_{tj} r_j$$

Subproblem (SUB7.2**)**: (related with decision variable x_{tj})

$$Z_{SUB2} = \min \sum_{t \in T} \sum_{j \in A} \left(\mu_j^1 \Phi_t^H (1 - 2h_{tj}) + \mu_j^4 \lambda_t + \mu_{jt}^5 d_{tj} + \mu_{jt}^6 \right) x_{tj} \quad \text{(SUB7.2)}$$

subject to: (7.9) and (7.13).

To solve this subproblem, we decompose this problem into |*T*| independent subproblems.

Subproblem (SUB7.2*t*):

$$Z_{SUB2t} = \min \sum_{j \in A} \left(\mu_j^1 \Phi_t^H (1 - 2h_{tj}) + \mu_j^4 \lambda_t + \mu_{jt}^5 d_{tj} + \mu_{jt}^6 \right) z_{tj} \qquad \text{(SUB7.2}t\text{)}$$

subject to: (7.9) and (7.13).

We define the coefficient of x_{tj} as $\text{coef}(x_{tj}) = \mu_j^1 \Phi_t^H (1 - 2h_{tj}) + \mu_j^4 \lambda_t + \mu_{jt}^5 d_{tj} + \mu_{jt}^6$ and calculate the value for each subproblem independently. Owning to Constraints (7.9) and (7.13), we assign the minimum coefficient x_{tj} to equal 1. That is, we home MT *t* to Sector *j* to minimize the objective value of (SUB7.2*t*).

Subproblem (SUB7.3): (related with decision variable g_j)

$$Z_{SUB3} = \min \sum_{j \in A} \left(\mu_j^3 Q(g_j, \beta_j) - \mu_j^4 g_j \right) \qquad \text{(SUB7.3)}$$

subject to:

$$0 \le Q(g_j, \beta_j) \le \overline{n}_j \qquad \forall j \in A. \qquad (7.14)$$

Without losing generality, we introduce configuration constraint (7.14) in this subproblem. Because the value of function $Q(g_j, \beta_j)$ is integer, we can exhaustively search the number of trunks for each sector and calculate the correspondent maximum traffic that can be served under certain capacity situation. Calculate the objective value by $\mu_j^3 Q(g_j, \beta_j) - \mu_j^4 g_j$ and select the minimum objective value case as our final decision.

Subproblem (SUB7.4): (related with decision variable f_i)

$$Z_{SUB4} = \min \sum_{i \in F'} \left(\Delta_F - \sum_{j \in A} \mu_{ji}^7 \right) f_i \qquad \text{(SUB7.4)}$$

subject to: (7.11).

We arrange augmentation channel order in ascending order of $\text{Coef}(f_i) = \Delta_F - \sum_{j \in A} \mu_{ji}^7$. To minimize the objective value of (SUB7.4), we assign the decision variable f_i to equal 1 if its coefficient is negative and 0 otherwise.

7.3.2 The Dual Problem and the Subgradient Method

According to the weak Lagrangean duality theorem [15][24], $Z_{D1} = \max Z_{LR1}(\mu_j^1, \mu_{ji}^2, \mu_j^3, \mu_j^4, \mu_{jt}^5, \mu_{jt}^6, \mu_{ji}^7)$ is a lower bound on Z_{IP1} for any $\mu_j^1, \mu_{ji}^2, \mu_j^3, \mu_j^4, \mu_{jt}^5, \mu_{jt}^6, \mu_{ji}^7 \geq 0$. The following dual problem (D7.1) is then constructed to calculate the tightest lower bound [21].

Dual Problem (D7.1):

$$Z_{D1} = \max Z_{LR1}(\mu_j^1, \mu_{ji}^2, \mu_j^3, \mu_j^4, \mu_{jt}^5, \mu_{jt}^6, \mu_{ji}^7)$$

subject to:

$$\mu_j^1, \mu_{ji}^2, \mu_j^3, \mu_j^4, \mu_{jt}^5, \mu_{jt}^6, \mu_{ji}^7 \geq 0$$

In this dual problem, let a ($|C| \times (3 + 2|F| + 2|T|)$)-tuple vector χ be a subgradient of problem $Z_{LR1}(\mu_j^1, \mu_{ji}^2, \mu_j^3, \mu_j^4, \mu_{jt}^5, \mu_{jt}^6, \mu_{ji}^7)$. In iteration k of the subgradient method, the multiplier vector $\pi = (\mu_j^1, \mu_{ji}^2, \mu_j^3, \mu_j^4, \mu_{jt}^5, \mu_{jt}^6, \mu_{ji}^7)$ is updated by $\pi^{k+1} = \pi^k + \xi^k \chi^k$. The step size ξ^k is determined by $\xi^k = \varsigma \frac{Z_{IP1}^h - Z_{D1}(\pi_k)}{\|\chi^k\|^2}$, where Z_{IP1}^h is the primal objective function value from a heuristic (an upper bound on Z_{IP1}) and ς is a constant between zero and two [25][30]. Computational performance and theoretical convergence properties of the subgradient method are discussed in Held, Wolfe and Crowder [25] and on non-differentiable optimization [30].

7.3.3 Getting Primal Feasible Solutions

When we use Lagrangean relaxation method as our solution approach to solve the problem, we get not only a theoretical lower bound of primal solutions but also some hints in the process of solving dual problem iteratively. We group three kinds of channels: (1) existing channels for each sector, (2) licensed channels in the system and (3) augmentation channels. We propose an efficient heuristic algorithm to get primal feasible solutions, which is denoted as Algorithm *A*.

- **Algorithm *A*:**

Step 1. Home all MTs to its original home sector. Aggregate the total traffic load of each sector to calculate the minimum required channels. If any sector violates its configuration constraint, go to Step 2 to rehome its slave MT.

Step 2. Arrange all slave mobiles in ascending order of its rehome cost for the infeasible sectors. For each mobile *t*, arrange the homing sequence in ascending order of the coefficients $\text{Coef}(x_{tj}) = \mu_j^1 \Phi_t^H (1-2h_{tj}) + \mu_j^4 \lambda_t + \mu_{jt}^5 d_{tj} + \mu_{jt}^6$ and try to rehome this MT sequentially.

Step 3. To satisfy Constraints (7.9) and (7.13), we select the minimum coefficient sector as our first candidate home and check the configuration constraint. If this homing decision violates the configuration constraint, try to home to the next sector until homing MT *t* to one candidate home correctly.

Step 4. For each sector *j*, aggregate the total traffic load to calculate the minimum required channels and derive the required minimum radius of this sector.

Step 5. Apply load-balance approach to arrange sectors in descending order of minimum required channels as our sector order. Select the first one as our target sector to assign channels.

Step 6. For each sector, arrange existing channel in ascending order of the coefficient value that is calculated by $\text{Coef}(y_{ij}) = \mu_j^1 \Phi_i^F (1-2z_{ij}) - \mu_j^3 + \mu_{ji}^2 (G_j - 1/\gamma_j)$ $-\sum_{t\in T} \mu_{jt}^6 k_{tj} + \sum_{j'\in A} \left(\mu_{j',(i-1)}^2 \theta + \mu_{j'i}^2 + \mu_{j',(i+1)}^2 \theta\right)\left(r_j / D_{j'j}(r_{j'})\right)^{\alpha_j}$ as licensed channel order.

Step 7. For the existing channels, check the QoS constraint of target sector in the licensed channel order and then assign the existing channel on the target sector.

Step 8. If the call-blocking probability constraint is still not satisfied, assign feasible licensed channels to the target sector and go to Step 5 to process next sector.

Step 9. If all of the sectors satisfy the call-blocking probability constraint, finish this program and one feasible solution is found. Otherwise, if there are existing channels in the system, go to Step 3 to assign existing channels.

Step 10. If re-assignment and power control cannot satisfy the network, arrange the augmentation channels in ascending order of $\text{Coef}(y_{ij}) = \mu_{ji}^7 - \mu_j^3 - \sum_{t\in T} \mu_{jt}^6 k_{tj}$ $\sum_{j'\in A} \left(\mu_{j',(i-1)}^2 \theta + \mu_{j'i}^2 + \mu_{j',(i+1)}^2 \theta\right)\left(r_j / D_{j'j}(r_{j'})\right)^{\alpha_j} + \mu_{ji}^2 (G_j - 1/\gamma_j)$ as augmentation channel order and begin to augment additional channels.

Step 11. For each augmentation channel, adopt the load-balance approach as sector order and check the QoS constraint to ensure that it does not violate QoS constraint of existing channels.

Step 12. Accumulate the license fee of total augmentation channels in this system as our objective value of this feasible solution.

7.4 Computational Experiments

Owing to the complexity of this problem, we cannot find tighter lower bound by solving dual problem. That is because the cost function plays an important role in affecting the duality gaps of (IP7.1). In order to prove that our LR-based algorithm is good enough, we also implement a primal heuristic to compare with our algorithm.

7.4.1 Primal Heuristic

In the previous section, we use some LR-based heuristics to determine (1) homing subproblem, (2) power control subproblem, (3) channel assignment subproblem and (4) channel augmentation subproblem. Contrarily, we use an intuitive thought to determine them in this primal algorithm. We adopt shortest homing policy to determine rehoming decisions. That is, all mobiles first home to its original home sector. If any sector violates configuration constraint, rehome its slave mobiles to candidate homes in the shortest first order. According to the slave mobiles in each sector, we can determine the transmission power of each sector in order to minimize inter-cell interference. Then, we also apply most-capacity-requirement-first policy to become our sector order. In this heuristic, we apply channel identifier as our channel order and begin to solve channel assignment and augmentation subproblems as LR-based approach. For convenience, we denote this heuristic as Heuristic *PH*.

7.4.2 Lagrangean Relaxation Based Algorithm

When solving Lagrangean relaxation problem, we provide an iterative LR-based algorithm to get primal feasible solutions. In each iteration, we apply Algorithm *A* as our solution approach to get primal feasible solutions. For convenience, we denote it as Algorithm *LR* and show as follows:

Step 1. Read configuration file to construct BSs, MTs and system information.

Step 2. Calculate constant parameters, initialize Lagrangean multipliers and assign Lagrangean relaxation improvement counter to equal 30.

Step 3. Apply primal heuristic to find a feasible solution. This objective value can be adopted as our initial upper bound of this planning problem.

Step 4. Solve Lagrangean relaxation problem by optimally solving the sub-problems of SUB7.1, SUB7.2, SUB7.3 and SUB7.4 to get the minimum objective value of Z_{LR1} according to given multipliers.

Step 5. Get primal feasible solutions through the proposed LR-based algorithm, which is Algorithm *A*, and calculate the total licensed fee of augmentation channels as a candidate upper bound of the problem, denoted as Z_{IP1}.

Step 6. If Z_{LR1} is larger than the existing lower bound Z_{LR1}*, we assign Z_{LR1}* to equal Z_{LR1}. If Z_{IP1} is smaller than the existing upper bound Z_{IP1}*, we assign Z_{IP1}* to equal Z_{IP1} and reset the improvement counter. Otherwise, we decrease the improvement counter by one.

Step 7. We calculate the gap between upper bound and lower bound to determine the stop criteria. If the gap is smaller than 5%, we can stop this program and claim that we find the near optimal solution to this problem. Otherwise, adopt subgradient method to calculate step size and adjust Lagrangean multipliers.

Step 8. Increase the iteration counter by one. If interaction counter is over maximum iteration of system, stop this program. That is, Z_{IP1}* is our best feasible solution. Otherwise, go to step 5.

7.4.3 Experiment Results

In the experiments, the Algorithm *LR* is performed on a sectorization scenario of network. The given parameters attenuation factor α_j is 4, CIR threshold γ_j is 9 dB, ACI ratio θ is 1/8, cost functions of Φ_i^F Φ_t^H Δ_F is 2000, 10000 and 200000, respectively. The test network is randomly generated by the network-planning problem in Chapter 5. The test scenario has 10 BSs constructed by 12 sectors and 20 MTs. The number of existing channels in the system is 53 and the number of total available channels is 150.

For experiment purpose, we introduce a violation degree of average traffic on the test network. We define the violation degree of average traffic as $\lambda_t(v) = \lambda_t \times (1 \pm v\%)$. We experiment three violation degrees, which are 0%, 50% and 100%. We list the experiment results of λ_t =2.75 and 3.0 in Table 7.3 and 7.4 respectively. In the computational experiments, our proposed Algorithm *LR* can achieve up to 50% improvement of total augmentation cost of network-servicing algorithm.

After performing on several randomly generated traffic violation cases, we can find that the servicing policies will be applied first when traffic load becomes unbalanced or when traffic distribution change against initial status on network-planning period. Algorithm *LR* can find feasible solutions under these kinds of violation cases. The network-servicing algorithm will increase the modification cost by applying channel reassignment, rehoming and power control mechanisms without augmenting any additional channel. Once the traffic demand grows, wireless networks become infeasible. Network sizing scheme must be applied by augmenting another available channels in this network.

All the experiments are performed on a PC with a Pentium IV 2.0 GHz CPU and 1.0 GB DRAM. The operating system running in this computer is Microsoft Windows 2000 Server. The code is written in C language and is complied by Microsoft Visual C++.

On average, Algorithm *LR* takes 85 seconds for running 1000 iterations to find out a better feasible solution and only uses half the number of the available channels. Because the license fee of augmentation channel dominates the cost structure of this problem and it becomes the objective of proposed formulation, using Algorithm *LR* can reduce network augmentation cost up to $200,000 in 70 seconds.

7.5 Concluding Remarks

In this chapter, we identify the network-servicing problem in the wireless communication networks. By introducing the channel reassignment, augmentation, homing and transmission power control mechanisms in wireless communication networks, we can alleviate the performance exceptions due to traffic distribution change and/or traffic growth. Channel reassignment may be required in a wireless communication network when channel interference and/or the distribution of traffic demand changes. Like channel reassignment, sector transmission power control and homing mechanisms are also effective and economical measure to alleviate performance problems. However, when the traffic demand exceeds a critical point and the current network capacity becomes insufficient, channel augmentation is required despite the application of the above-mentioned two cost-effective measures.

We formulate this problem as a combinatorial optimization problem, where the objective function is to minimize the channel augmentation cost subject to configuration, capacity, QoS constraints and call-dropping constraints. The basic solution approach to the algorithm development is Lagrangean relaxation. In computational experiments, the proposed algorithm is shown to be efficient and effective. The proposed algorithm can achieve up to 66.67% improvement of the total channel augmentation fee from the primal heuristic.

Table 7.3: Channel augmentation cases with different violations

λ_t	V	R	LB	Gap	*PH*	Modify-cost	*LR*	Modify-cost	Improve	T
2.75	0	0	2.5994e-003	5.00e+010%	1.30e+006	7.20e+004	1.30e+006	6.80e+004	0.00%	58
2.75	50%	1	3.4038e-003	4.99e+010%	1.90e+006	7.20e+004	1.70e+006	7.00e+004	10.53%	59
2.75	50%	2	6.3007e-004	2.06e+011%	1.50e+006	6.60e+004	1.30e+006	6.60e+004	13.33%	59
2.75	50%	3	8.1944e-004	2.07e+011%	2.30e+006	7.00e+004	1.70e+006	7.40e+004	26.09%	58
2.75	100%	1	3.3828e-004	2.07e+011%	1.10e+006	7.80e+004	7.00e+005	8.20e+004	36.36%	64
2.75	100%	2	8.2391e-004	2.06e+011%	1.90e+006	8.00e+004	1.70e+006	8.20e+004	10.53%	62
2.75	100%	3	3.3741e-004	2.07e+011%	8.00e+005	8.80e+004	7.00e+005	9.00e+004	12.50%	60

Table 7.4: Channel rearrangement and augmentation cases with different violations

λ_t	V	R	LB	Gap	*PH*	Modify-cost	*LR*	Modify-cost	Improve	T
3	0	0	0.0000e+000	0.00e+00%	0.00e+000	0.00e+000	0.00e+000	0.00e+000	0.00%	0
3	50%	1	8.5362e-005	2.34e+011%	3.00e+005	2.80e+004	2.00e+005	2.80e+004	33.33%	68
3	50%	2	8.4638e-005	2.36e+011%	3.00e+005	2.60e+004	2.00e+005	2.80e+004	33.33%	67
3	50%	3	4.2423e-005	2.36e+011%	3.00e+005	2.00e+004	1.00e+005	2.20e+004	66.67%	69
3	100%	1	8.5338e-005	2.34e+011%	3.00e+005	4.40e+004	2.00e+005	4.40e+004	33.33%	72
3	100%	2	2.1163e-004	2.36e+011%	6.00e+005	7.00e+004	5.00e+005	7.00e+004	16.67%	64
3	100%	3	8.4593e-005	2.36e+011%	3.00e+005	5.80e+004	2.00e+005	5.80e+004	33.33%	68

8. Conclusion and Future Researches

8.1 Summary

In this dissertation, we study the resource allocation and management issues in channelized wireless communication networks. Our research scope consists of three research modules (the network planning, performance assurance/optimization and network-servicing modules). We also identify the research issues for performance optimization and network servicing modules. We formulate these problems as combinatorial optimization problems. We develop several integer-programming algorithms to model the network planning, performance optimization and network servicing problems. The solution approach is based on Lagrangean relaxation method. We summarize this dissertation as follows.

1. **Flexible channel assignment problem:** we study the flexible channel assignment problem in wireless communication networks where the total call-blocking rate is set to be the key performance indicator. Both CCI and ACI are considered in the generic channel interference model to ensure communication QoS. In addition, irregular rather than regular cell configuration and sectorization are considered. We formulate this problem as an integer-programming problem and develop an LR-based algorithm to deal with this channel assignment problem. In computational experiments, the proposed algorithm is shown to be far superior to a number of sensible heuristics. It can find

feasible solutions with less number of channels and achieve up to 99.42% and 58.15% improvement of the total call-blocking rate.

2. **Sequential homing problem:** we study the key issues of sequential homing problem for multiple-connectivity wireless communication networks. For generalization purpose, we formulate the sequential homing problem as a sequential routing algorithm. The purpose of this algorithm is to decide realtime connection-setup sequence according to the given average traffic demands and candidate routes information. The emphasis of this work is to develop a centralized sequential routing algorithm to support distributed realtime homing in well-designed multiple-connectivity communication networks. We successfully apply this algorithm as one of our kernels for resource allocation and management in reliable wireless networks. The routing information can be used to combine with admission control, resource allocation, connection setup and QoS assurance. In the computational experiments, the proposed LR-based algorithms achieve up to 99.98% improvement of the total call-blocking rate from the four proposed primal heuristics and the Markov-decision algorithm.

3. **Network planning module:** the proposed LR-based algorithm is the first attempt to consider the integrated network design problem with whole factors jointly and formulate it rigorously. Due to the time variance and unstable properties of wireless networks, the proposed algorithm is helpful to design high-reliability wireless networks. We identify reliability issue of channelized wireless communication networks by introducing customized multiple-connectivity effect. The proposed algorithm not only designs a multiple connectivity network but also guides to route MT among its candidate homes sequentially. In the computational experiments, we compared the proposed algorithm with the power dominant heuristic on test networks. The proposed algorithm can achieve up to 36.56% improvement of the total cost of network design problems.

4. **Performance assurance and optimization module:** we consider the performance optimization problem for channelized wireless communication networks. Instead of adopting DCA policy, we develop a FCA model to combine with centralized sequential homing mechanism to support realtime admission control, channel assignment and homing issues to maximize average system performance. Further, we study the effect of adjustable channel separation together on accounts of generic channel interference on different propagation environments. The emphasis of this work is to develop a centralized sequential homing and FCA algorithm to support realtime distributed admission control. In the computational experiments, the proposed channel separation is better than GSM system. We also compare the proposed algorithm with the power dominant heuristic on test networks. The proposed algorithm achieve on average up to 99.9% improvement of the total call-blocking rate.

5. **Network servicing module:** we identify the resource rearrange and augmentation problem in the wireless communication networks. By introducing the channel reassignment, augmentation, homing and transmission power control mechanisms, we can alleviate the performance exceptions due to traffic distribution change and/or traffic growth. We formulate this problem as a combinatorial optimization problem. The solution approach is Lagrangean relaxation. In computational experiments, we can observe that channel reassignment may be required when channel interference and/or the distribution of traffic demand changes. Sector transmission power control and homing mechanisms are also effective and economical measures to alleviate performance problems. However, when the traffic demand exceeds a critical point and the current network capacity becomes insufficient, channel augmentation is required despite the application of the above-mentioned two cost-effective measures. The proposed algorithm is shown to be efficient and effective. It can achieve up to 66.67% improvement of the total channel augmentation fee from the primal heuristic.

8.2 Future Research

After completing this dissertation, we feel that there is still much to be explored. In this section, we outline several research areas that are worthy of further investigation.

Emerging requirements for higher rate data services and better spectrum efficiency are the main drivers identified for the third-generation (3G) mobile systems. Recently, extensive investigations have been carried out into the application of a code division multiple access (CDMA) system for IMT-2000/UMTS. The future research will extend the research domain to the 3G wireless networks with multimedia applications [81].

In resource allocation and management issues, there is a need to exploit the similarity of constraints that characterize assignments within and across the time, frequency and code domains. This problem arises in a spread-spectrum based access scheme in which orthogonal CDMA codes are to be assigned to links. For collision free transmissions, no two links sharing the same node are assigned the same code. In graph-theoretic terms, this is the well-know edge-coloring problem [73].

To provide different classes of multimedia traffic and supporting user mobility, we must exploit the multimedia traffic models and the mobility effects. Because the wideband CDMA system is essentially limited by the multiple access interference among active users, performance can be assessed in terms of blocking probability and average number of users per cell taking into account user mobility and traffic characteristics [67].

The CDMA system is interference-limited system in which link performance depends on the ability of the receiver to detect signal in presence of interference. In network planning issues, because the capacity of a CDMA system normally depends upon the uplink capacity, we must exploit uplink radio characteristics and analytical models to calculate the capacity of each BS supporting 3G services [20].

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Appendix A Acronyms and Notation

A.1 Acronyms

ACC	adjacent channel constraint
ACI	adjacent channel interference
BS	base station
CCI	co-channel interference
CIR	carrier-to-interference ratio
CSC	co-site constraint
DCA	dynamic channel assignment
FCA	fixed channel assignment
FlCA	flexible channel assignment
GoS	grade of service
GSM	the global system for mobile communication
HCA	hybrid channel assignment
LR	Lagrangean relaxation
MT	mobile terminal
MTSO	mobile telephone switching office
NCI	near channel interference
NFD	net filter discrimination
O-D	origin-destination
PDF	probability density function
QoS	quality of service

A.2 Notation

Notation	Description
A	the set of sectors
B_{ts}	call-blocking probability for the s^{th} candidate homing policy for t which belongs to discrete set $B_{ts} \in K_{ts} = \{0, 0.01, 0.02, ..., \overline{B}_{ts}\}$
C	the set of BSs in the system
$D_{jj'}(r_j)$	minimum distance between interested Sector j and interfering Sector j' under the condition of the transmission radius of Sector j
$E(n_{ja}, g_{ja})$	blocking probability function for Sector a of BS j, which is a Erlang-B formula of traffic demand and available number of channels.
F	the set of available channels
F'	the set of available augmentation channels
G_{ja}	an arbitrarily large number for Sector a of BS j
K_t	connectivity requirement of MT t to connect with K_t candidate homes
L	the set of links
M	the set of all kinds of sectorization types
N	total number of available channels
P_w	the set of paths which can support requirement of OD pair w
$Q(g_j, \beta_j)$	minimum number of channels required for traffic demand g_j such that the call-blocking probability shall not exceed β_j
R_{tj}	received power level of MT $t \in T$ from the downlink signal of Sector $j \in C$
S_t	the set of permutation for MT t which is integer value and $S_t = \{1, 2, ..., K_t\}$
T	the set of MTs

W	the set of O-D pairs
b_{tja}	blocking probability of Sector a on BS j which is referenced by MT t
c_{jm}	sectorization type m for BS j
d_{tj}	the distance between Sector j and MT t
e_{pl}	indicator function which is 1 if link l belongs to path p and 0 otherwise
f_i	licensed channel which is 1 if Channel i is installed and 0 otherwise
g_{ja}	aggregate flow on Sector a on BS $j \in C$ (in Erlang)
h_{tj}	the original homing relationship between MT t and Sector j
k_{tja}	decision function which is 1 if MT t can be served by Sector a of BS j and 0 otherwise
n_{ja}	number of channels assigned to Sector a of BS j
p_{ja}	effective isotropic radiated power (EIRP) of Sector a on BS j (in Watt)
r_j	transmission radius of Sector j
x_{tjas}	homing/routing decision variable which is 1 if Sector a of BS j is selected as the s^{th} candidate path of MT t and 0 otherwise
y_{ija}	decision variable for channel assignment for Sector a of BS j about Channel i
z_{ij}	indicator function which is 1 if existing Channel i is used by Sector j and 0 otherwise
α_j	attenuation factor (2< α <6) for Sector j
β_t	threshold of acceptable call-blocking probability
γ	threshold of acceptable CIR
δ	receiver sensitivity of each MT (in Watt)

$\theta(\Delta i)$	NFD ratio which is formed as a function of the channel separation (kHz) normalized to the bit-rate (bps)
π	the multiplier vector
λ_t	the mean traffic arrival rate of new traffic on location $t \in T$ (in Erlang)
ϕ_{tja}	path loss ratio of radio propagation from Sector (j,a) to MT t
ε_b	BS antenna height above local terrain height [m]
η_c	carrier frequency [MHz]
κ	free space wavelength [m]
σ_s	the angle between the street and the direct line from base to mobile
ϖ	the average longer paths between the buildings for oblique incidence
ρ	transmission bit rate
ξ	the step size used by subgradient method
χ	the subgradient vector
$\Psi(\eta)$	the filter characteristic on frequency η
Γ	cluster size
$\Delta_C(n_{ja})$	capacity cost function of equipments to assign n_{ja} number of channels
Δ_F	spectrum frequency license fee
Δ_m	cost of BS with configuration type m
Φ_j^A	the loss revenue limitation for Sector j to rearrange channel assignment and power level
Φ_i^F	loss of revenue for the decision of reassignment existing channel i
Φ_t^H	loss of revenue for the decision of re-homing MT t