針對下鏈路LTE-A網路所設計且以提昇傳輸速率為目標之資源管理技術

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摘　要

由於頻譜與能量資源的有限且珍貴，資源分配問題在近幾年越來越重要。然而，不恰當的資源分配會導致強烈的細胞間干擾，此干擾會嚴重的影響整體系統效能。因此在這篇論文中，我們將整個資源分配問題轉化為數學最佳化問題，且根據此最佳化問題提出解決策略。在聯合載波選擇與功率分配 JCP 策略中，通道選擇與功率分配將會在幾何程序 (Geometric Programming) 的轉化與干擾未知的假設下被聯合求解。然而，顧慮到 JCP 策略的高複雜度，提出另一個簡化策略 (JCP-S)。此策略將在干擾固定假設的最佳化問題中求解，期望能達到降低複雜度的效果。此外，儘管已經做出簡化，聯合問題依然是複雜的。因此，提出更簡化的 HCP 策略以及 HCP-S 策略。其概念是將整個聯合問題分解為兩個子問題，也就是說通道選擇和功率分配將根據所提之演算法被依序分別求解。最後，模擬結果顯示 JCP 策略的效能高於其他所提若干之簡化策略，且因為效能與複雜度的考量下，兩者間存在著權衡概念。

Rate-enhanced Resource Management for Downlink LTE-A Networks

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Abstract

Because of the scarcity of spectrum and energy resource, the problems about allocation of these resources become more and more important in recent years. However, inappropriate resource allocation may bring about high inter-cell interference which has a great effect on the performance of the entire system. Thus, in this thesis, we provide the optimal formulation of the resource allocation problem and proposed several schemes to solve this problem. In joint component carrier selection and power allocation (JCP) scheme, the channel and power resource are jointly solved based on geometric programming and the consideration of undeterministic interference term. Pondering on the high complexity and computational cost in JCP scheme, another simplified scheme, called JCP-S scheme, is proposed where the interference term is assume to be fixed with expectation to lower the complexity. Besides, on account of that the complexity is still high to solve problem from joint view, heuristic scheme, called HCP scheme and HCP-S scheme, are then proposed and try to separate the joint problem into two parts. In other words, channel selection and power allocation problems are solved according to the corresponding algorithms successively. Simulation results demonstrate that the data rate performance of JCP scheme is better than that of the other simplified schemes. However, there exists a trade-off between JCP scheme and the other simplified schemes considering the performance and the complexity.

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Chapter 1

Introduction

The long term evolution (LTE) and its advanced version LTE-A system, developed by 3rd generation partnership project (3GPP) as a mobile communication standard from the former 3G systems, has been proven that it can provide high data rate, high resource allocation efficiency, and larger transmission coverage. However, the first release of LTE, which is being described as 3.9G, cannot meet the requirements for 4G, such as peak data rates up to 1 Gbps in nomadic speed, defined by the International Telecommunication Union. For the purpose of pursuing higher data rate and spectrum efficiency in LTE-A system, the issues about allocating the two main kinds of radio resource, spectrum resource and power resource respectively, have become more and more important.

Orthogonal frequency division multiple access (OFDMA) technique, which is a multi-user version of orthogonal frequency division multiplexing (OFDM), has been well studied [1–3] and utilized in LTE downlink transmission. In the OFDMA structure, component carrier (CC) is the spectrum resource that can be allocated for data transmission in LTE-A network. The component carriers utilized in the LTE-A systems can be divided into two categories as follows. One is the primary component carrier (PCC) through which the user equipment (UE) handles the network entry process in the control channel. The PCC also contains the data channel which is used for data signal transmission. Each UE only has one CC as PCC which is chosen by its eNB, i.e. eNodeB which represents the base station in LTE system. The other one is secondary component carrier (SCC), which is mainly responsible for data transmission. Thus, SCC only includes data channel and eNB can choose many CCs as SCCs for its own UEs if necessary. It is allowed for eNB to select the CCs for transmission even though these CCs have been chosen by neighboring eNBs. This way would bring about a higher spectrum efficiency, but also cause enormous inter-cell interference which has a great influence on transmission data rate if the component carriers are not well-allocated. The 3GPP proposes two methods, inter-cell interference coordination (ICIC) [4] for LTE and its enhanced version eICIC [5] for LTE-A respectively, to reduce inter-cell interference by adaptive channel selection and power control. In [6, 7], component carriers are selected according to the background interference matrix (BIM), which records outgoing and incoming interference information to reduce inter-cell interference, and has not bad performance comparing to the methods proposed by 3GPP. Although these works introduce intuitive methods which effectively reduce the background interference on each component carrier, they aren't joint optimization considering channel selection and power allocation. Furthermore, in previous research works, the design rational of PCCs and SCCs selection algorithms are from eNB's viewpoint, i.e., all UEs in one eNB will be allocated with the same set of CCs as PCC and SCCs. Due to the lack of diversity in UEs, it is intuitive that this type of eNB-oriented CC selection will result in lower spectrum efficiency.

In order to meet the broadband requirement in 4G, carrier aggregation (CA) technique has been proposed in [8] to aggregate two or more component carriers (CCs), even if these CCs are not continuous in frequency domain, to support high data rate transmission. Referring to specification [9], each aggregated carrier is seen as a CC and can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz. Maximum of five component carriers can be aggregated, hence the maximum aggregated bandwidth is 100 MHz. However, compared to the situation that only one CC can be used for data transmission, the enlarged available bandwidth bring about a larger number of data channel allocative information transmitted in control channel. In other words, with limited resources in control channel, the maximum total number of data channels for data transmission one UE can use is constrained to the total resources it has in control region for transmitting data channels' allocative information. Therefore, how to allocate the resources in control channel to get higher transmission throughput in data channel is a new issue that should be considered in CC allocation problem since wide bandwidth transmission becomes available owing to CA technique.

Regarding power control, two common power control problems, sum rate maximization and sum power minimization, would be solved optimally when the optimization model has convex property. Unfortunately, the power optimization problem would become a non-convex problem while considering inter-cell interference. In [10], the required transmission power for UEs located at the cell center would firstly be determined by their proposed power allocation approach. Besides, using scheduling strategy, cell-edge UEs would only mutually interfered with the center UEs of neighboring eNB. Thus, the optimal power allocation problem for the cell-edge UEs would become a convex problem, which can be solved by the Lagrangian method. However, spectrum efficiency can be degraded by stipulating that only cell-edge UEs and theirs neibhboring eNBs' center UEs could select resource at the same time according to scheduling strategy. In addition, in [11], the resource allocation problem is divided into two parts, one is channel allocation and the other is power allocation. The power allocation is executed with channel allocation being determined. And in these two schemes, the interference term is considered to be deterministic in power optimization. In [12], even though the optimization is not concave, the optimal solution for power allocation is proven to be the same as the solution for the corresponding dual optimization problem when the problem satisfies time-sharing property. However, it only considers the problem for power allocation in the optimization. Furthermore, with no CA technique, all the schemes mentioned before don't consider the required transmission rate on PCC's control channel, who would be a constraint on the total data channels' rate as mentioned before.

In this thesis, optimization is formulated to maximize the total channel capacity on all data channels under the constraints of maximum transmission power and maximum number of data channels which is related to the resource allocation in control region. Firstly, a resource allocation scheme is proposed, called joint component carrier selection and power allocation (JCP) scheme which prefers to jointly solve the CC selection and power allocation. Secondly, in order to lower the high complexity in JCP scheme which consider underterministic interference, a simplified version of JCP (JCP-S) is proposed. Besides, considering the high complexity of the joint view, a heuristic component carrier selection and power allocation (HCP) shceme is proposed which divides the original optimization problem into two subproblems, which are channel selection and power allocation. In the first stage of HCP, a channel selection method is proposed to not only reduce the inter-cell interference but also to enhance the total UEs' data transmission rates. In the second stage of HCP, a methods is proposed, considering underterministic interference as in JCP, to solve power allocation with the channel allocation being known from the first stage. Moreover, seeing that the high computation cost when considering underterministic interference, another power allocation method is proposed with the concept of derterministic interference. And call the scheme a simplified version of HCP, i.e. HCP-S. At final, simulations will be performed to compare their performance under different environments and validate that the scheme in joint view can achieve better performance than that in divided view even though the high complexity in joint view. The comparisons between proposed schemes and other schemes mentioned before are shown in Table 1.1.

The rest of this thesis is organized as follows. Chapter 2 introduce the resource structure in LTE-A systems and formulates the complete resource allocation problem in optimization view. The proposed joint component carrier selection and power allocation (JCP) scheme and simplified version of JCP (JCP-S) are presented in Chapter 3. Next, the heuristic scheme (HCP) will be presented in Chapter 4. The simulation results and performance comparisons will be demonstrated in Chapter 5. Finally, Chapter 6 draws conclusion.

Table 1.1: Schemes comparison

	Allocation type	Channel allocation	Power allocation	Orientation
ICIC	Separated	Heuristic	Heuristic	Interference reduced
ACCS	Separated	Heuristic	Heuristic	Interference reduced
Scheme in [10]	Separated	Heuristic	Optimization	Rate maximized
Scheme in [11]	Separated	Heuristic	Optimization	Rate maximized
Scheme in [12]	Only power	No allocation	Optimization	Rate maximized
Proposed JCP	Joint	Optimization	Optimization	Rate maximized
Proposed HCP	Separated	Heuristic	Optimization	Rate maximized

Chapter 2

System Model and Problem Formulation

2.1 Downlink Scenario for LTE-A System

As shown in Fig. 2.1, a multi-cell downlink homogeneous LTE-A system is considered and all eNBs are equipped with omnidirectional antennas. The cell deployment follows the wrap around topology [13] and each cell contains a centering eNB with a number of serving static user equipments (UEs). Under the consideration of interference from other eNBs, called inter-cell interference and represented as dotted line in Fig. 2.1, each eNB should determine allocation in control and data region for each integrated resource unit on each CC, called physical resource block pair (PRBP) in LTE, to its own UEs and decide how much power will be transmitted on the data region for each PRBP if used. Besides, there are no specific rules in specification that regulate all UEs belonging to the same serving eNB should select the same resource for transmission. For more flexibility and higher spectrum efficiency, assume that the UEs belonging to the same serving eNB can select different CCs as their PCC and SCCs. Moreover, in order to avoid the intra-cell interference which would greatly reduce the channel capacity if occurred, the specification regulates that, not only in control region but also in data region for one PRBP, the UEs belonging to the same serving eNB cannot select the same resource for transmission. In other words, in both region for one PRBP and for one eNB, a resource can be at most allocated to one UE simultaneously.

In order to resist the outside interference, the coding and modulation techniques have been proven that it can effectively reduce the bit error rate (BER). According to different conditions of channel quality, UEs can decide the best channel quality indication (CQI) index so that the transport error probability not exceeding 10 percentage. In the specification, the modulation and coding scheme (MCS) is developed for the purpose of selecting appropriate code rate and modulation to transmit data according to the CQI index. More explicitly, when encountering bad channel quality, it is prefer to select the scheme with low code rate, i.e. add more redundant bits to resist the strong interference, and noise-resisted modulation (e.g. QPSK) to transmit data. On the other hand, since guaranteeing the BER is not hard to achieve under condition of good channel quality, the scheme with high code rate and high-rank modulation (e.g. 16-QAM, 64-QAM) can be used to increase the transmission rate.

As shown in Fig. 2.2, in time domain, a downlink transmission frame is equally divided into 10 subframes and each subframe contains two time slots. Each slot has $N_s = 7$ OFDM symbols. In frequency domain, the total bandwidth of a component carrier is equally divided into numerous subcarriers (SCs) and each subcarrier has 15 (kHz). According to the LTE-A specification [14], the size of least resource unit, called resource element (RE), is 1 subcarrier and 1 OFDM symbol. Further, the size of physical resource block (PRB) is $V = 12$ subcarriers and 7 OFDM symbols. The integrated resource unit is a pair of PRB, i.e. PRBP. Assume that the first N_c OFDM symbols in a PRBP are responsible for control signal transmission, and the rest $2N_s - N_c$ OFDM symbols are responsible for data signal transmission. That is to say, the size of basic resource unit for allocation in control region is $V = 12$ subcarriers and N_c OFDM symbols, and call it control resource unit. The size of basic resource unit for allocation in data region is $V = 12$ subcarriers and $2N_s - N_c$ OFDM symbols, and call it data resource unit. As a result, control channel transmission and data channel transmission can be separated by time division duplex (TDD) technique. Then, in frequency domain, assume that there are total J component carriers in the system and each CC has R PRBPs in one subframe. Note that since the information transmitted in control channel is so important that it influences whether the whole system functions properly or not, these information should be transmitted carefully even without loss. As shown in Fig. 2.3, there are several types of control channels in the downlink control region, including physical downlink control channel (PDCCH), physical HARQ indicator channel (PHICH), physical control format indicator channel (PCFICH), etc. Each type of control channel has its own responsible functions. For instance, the PDCCH is responsible for transmitting the allocative information of physical downlink shared channel (PDSCH), which is the main type of data channel in data region. In other words, the information records that which PDSCH should be assigned to which UE is all transmitted in the PDCCH. Besides, there are several types of physical signal transmitted on some control channels, like reference signal (RS) which is mainly responsible for channel estimation.

2.2 Problem Formulation for Resource Allocation in LTE-A System

As mentioned before, the allocative information of PDSCH is transmitted by PDCCH. Assume that r is the ratio of resources which are responsible for transmitting allocative information of PDSCH in control region. Considering the importance of control signal and in order to guarantee the control signal can be transmitted to received terminals with low error probability, the

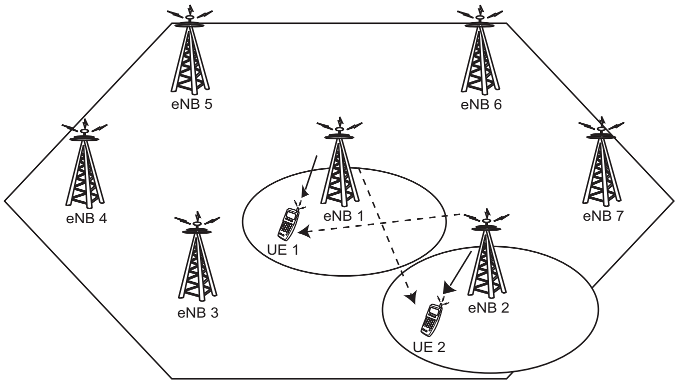

Figure 2.1: Downlink LTE-A system.

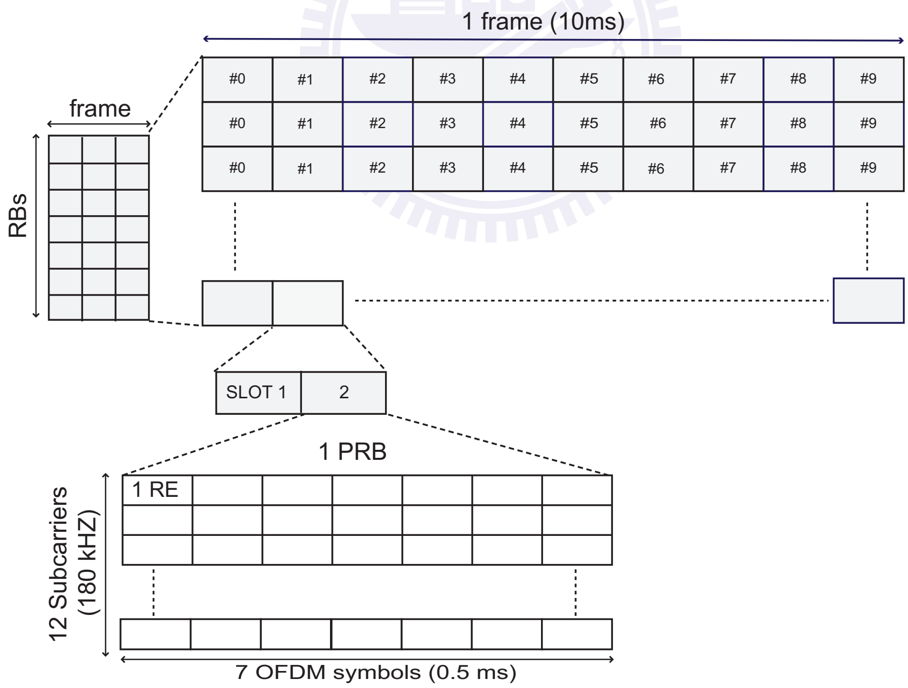

Figure 2.2: Resource structure for downlink LTE-A system.

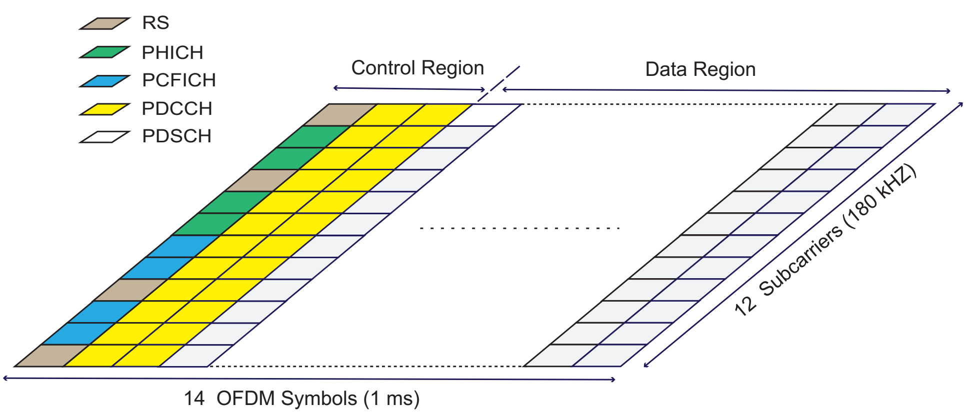

Figure 2.3: Mapping of PCFICH, PHICH, PDCCH, PDSCH in one PRB pair.

scheme with low code rate and noise-resisted modulation is more preferable. Assume that the QPSK modulation, which can transmit at most $A = 2$ bits on each resource element, and code rate κ is used in the control region, so that the code efficiency is $\nu = \frac{2\cdot\kappa}{1024}$. And the maximum total bit rate that a PRBP can provide for allocative information of PDSCH in one subframe can be represented as $\zeta = A \cdot V \cdot N_c \cdot r$ (Kbps). That is to say, what modulation and code efficiency is used influences the capability of one PRBP to transmit allocative information in control region for data channel.

A bitmap, one scenario for resource allocation in data region, is used to indicate the resource block groups (RBGs) where a RBG is a set of consecutive data resource units. Assume a resource block group contains G consecutive data resource units and then the total number of RBGs in the whole component carriers can be represented as $\phi = \lfloor \frac{J\cdot R}{G} \rfloor + 1$. To make an associative connection to the PDCCH in control region, the RBG is allocated to the UE if the corresponding bit value in the PDCCH is 1. For instance, if an UE wants to take all of the RBGs as PDSCH to transmit data, the UE needs $\varphi = \phi \cdot \frac{1}{\nu}$ bits resource space in PDCCH to transmit PDSCH allocative information in one subframe, i.e. needs rate φ (Kbps) in PDCCH. In other words, allocating one RBG as PDSCH to an UE at least needs $\frac{1}{\nu}$ (Kbps) rate resource in PDCCH. And the maximum number of RBGs that an UE can use for PDSCH is determined by how much resource the UE gets in the control region, i.e resource in control region of one PRBP can provide ζ (Kbps) for transmitting allocative information of data channel. Thus, the resource allocation in control region has great effects on the resource allocation in data region and the final performance of system data rate.

The main goal is to maximize the total channel capacity in all data channels under the constraint of maximum transmission power and the constraint of maximum data channel's number each UE can get in data region according to the resource allocation in control region. In other words, the target in our optimization problem is to acquire the channel allocation in both regions and the power allocation on each channel in order to maximize the total data transmission rate on all data channels. Denote $\bar{C}_{j,s,k}^{i,(D)}$ as the channel capacity of kth UE in eNB i on the subchannel s of the CC j in data region. It is assumed that the total numbers of eNBs in the LTE-A network are M and the set of all eNBs is denoted as $\mathbf{M}$. There are K UEs in each eNB and $\mathbf{K}$ represents the set of all UEs. The sets of all CCs and all subchannels are denoted as $\mathbf{J}$ and $\mathbf{S}$, respectively. For simplicity, assume that the RBG size G equals to 1. Namely, one data resource unit is the allocative subchannel unit in data region, and one control resource unit is the allocative subchannel unit in control region. Moreover, $\bar{\rho}$ is the channel selection indicator and is defined as follows

$$\bar{\rho}_{j,s,k}^{i,(C)} = \begin{cases} 1, & \text{if UE } k \text{ in eNB } i \text{ selects subchannel } s \text{ of the CC } j \text{ as CCH} \\ 0, & \text{otherwise} \end{cases} \tag{2.1}$$

and

$$\bar{\rho}_{j,s,k}^{i,(D)} = \begin{cases} 1, & \text{if UE } k \text{ in eNB } i \text{ selects subchannel } s \text{ of the CC } j \text{ as SCH} \\ 0, & \text{otherwise} \end{cases} \tag{2.2}$$

Note that $\bar{\rho}_{j,s,k}^{i,(C)} \in \bar{\boldsymbol{\rho}}^{(\boldsymbol{C})}$ and $\bar{\rho}_{j,s,k}^{i,(D)} \in \bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}, \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K}$.

The bar means the indicator belongs to discrete domain. And define

$$\delta_{j,k}^{i,(C)} = \begin{cases} 1, & \text{if } \sum_{s=1}^{R} \bar{\rho}_{j,s,k}^{i,(C)} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{2.3}$$

From the viewpoint of CC's categories, the component carrier j with $\delta_{j,k}^{i,(C)} = 1$, the subchannel s on this CC with $\bar{\rho}_{j,s,k}^{i,(D)} = 1$, and the subchannel s on this CC with $\bar{\rho}_{j,s,k}^{i,(C)} = 1$ can be view as the PCC, this PCC's data channel, and this PCC's control channel of kth UE in eNB i, respectively. The remain component carrier $j^{'}$ with $\delta_{j^{'},k}^{i,(C)} = 0$ can be view as the SCC of kth UE in eNB i if there exist any subchannel s with $\bar{\rho}_{j^{'},s,k}^{i,(D)} = 1$. With the notations defined above, the optimization problem can be formulated as

$$\max_{\bar{\boldsymbol{\rho}}^{(C)},\bar{\boldsymbol{\rho}}^{(D)},\mathbf{P}} \quad \sum_{i=1}^{M}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{s=1}^{R} \bar{C}_{j,s,k}^{i,(D)} \tag{2.4}$$

subject to:

$$\bar{\rho}_{j,s,k}^{i,(C)} \in \{0,1\}, \bar{\rho}_{j,s,k}^{i,(D)} \in \{0,1\}, \qquad \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K} \tag{2.5}$$

$$\sum_{j=1}^{J} \delta_{j,k}^{i,(C)} = 1, \qquad \forall i \in \mathbf{M}, \forall k \in \mathbf{K} \tag{2.6}$$

$$\sum_{k=1}^{K} \bar{\rho}_{j,s,k}^{i,(C)} \leq 1, \sum_{k=1}^{K} \bar{\rho}_{j,s,k}^{i,(D)} \leq 1 \qquad \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S} \tag{2.7}$$

$$\sum_{j=1}^{J}\sum_{s=1}^{R}\sum_{k=1}^{K} P_{j,s,k}^{i} \leq P_{max}, \qquad \forall i \in \mathbf{M} \tag{2.8}$$

$$\sum_{j=1}^{J}\sum_{s=1}^{R} \bar{\rho}_{j,s,k}^{i,(D)} \leq \frac{\zeta}{\nu} \cdot \sum_{j=1}^{J}\sum_{s=1}^{R} \bar{\rho}_{j,s,k}^{i,(C)}, \qquad \forall i \in \mathbf{M}, \forall k \in \mathbf{K} \tag{2.9}$$

The main goal is to find the power set $\mathbf{P}$, channel selection set for control region $\bar{\boldsymbol{\rho}}^{(C)}$, and channel selection set for data region $\bar{\boldsymbol{\rho}}^{(D)}$ respectively that maximize the total channel capacity. Equation (2.6) means that each UE can select only one CC as its control CC, i.e. PCC. In order to avoid the occurrence of intra-cell interference, the constraint in equation (2.7) represents that one subchannel can be allocated to at most one UE in an eNB. The $P^i_{j,s,k}$ in equation (2.8) represents the transmission power of kth UE in eNB i on the subchannel s of the CC j which belongs to the set $\mathbf{P}$ and P_{max} denotes the maximum allowed transmission power for each eNB. The term $\frac{\zeta}{\nu}$ in equation (2.9) represents the equivalent total subchannels' amount in data region that one subchannel in control region can guarantee and provide for transmitting allocative information. This constraint means that the total amount of subchannels, which are selected by an UE for data channels, should not exceed the maximum number which is guaranteed by the total resource the UE gets in control channel. In addition, observing the optimization problem, the way to measure the rate in control channel is from the perspective of practical data rate regardless of the channel capacity. As mentioned before, the reason is that, in general, the most important thing concerned in control channel is how to transmit the control signal with low error probability instead of how to increase the transmitting data rate. So the MCS with low error probability is assumed to be used in control channel and bring about the viewpoint of practical data rate. Besides, according to Shannon capacity theory, the transmission rates on data channels in equation (2.4) can be derived as

$$\bar{C}^{i,(D)}_{j,s,k} = \frac{2N_s - N_c}{2N_s} \cdot B \cdot \log_2(1 + S^{i,(D)}_{j,s,k}) \quad \text{(bits/s)} \tag{2.10}$$

where the term $\frac{2N_s-N_c}{2N_s}$ specify that the capacity belongs to data region. B in (2.10) is the bandwidth of one subchannel, i.e. 180kHZ as shown in Fig. 2.2. The kth UE's signal to interference plus noise ratio (SINR) in eNB i on the subchannel s of the CC j in data region is denoted as $S^{i,(D)}_{j,s,k}$, and can be written as follow

$$S^{i,(D)}_{j,s,k} = \frac{\bar{\rho}^{i,(D)}_{j,s,k} \cdot P^i_{j,s,k} \cdot g^{i,i}_{j,s,k}}{\Gamma \cdot (N_0 + I^{i,(D)}_{j,s,k})} \quad , \quad I^{i,(D)}_{j,s,k} = \sum_{q \neq i} \sum_{z=1}^{K} \bar{\rho}^{q,(D)}_{j,s,z} \cdot P^q_{j,s,k} \cdot g^{q,i}_{j,s,k} \tag{2.11}$$

The $\bar{\rho}_{j,s,k}^{i,(D)}$ indicate that whether the subchannel is selected for data transmission or not, i.e. the capacity on this subchannel equals to zero if not. According to channel model in [15] which considers the pathloss, shadowing, and fading effects, the parameter $g_{j,s,k}^{i,i'}$ in (2.11) is defined to represent the channel gain from eNB i to kth UE of eNB i' on the subchannel s of the CC j, and the channel gains of all the communication links are assume to remain constant in one downlink transmission frame. Assume $\boldsymbol{g}$ represent the set of all channel gain's information. The parameter $\Gamma = -\ln(5BER)/1.5$ in (2.11) can be obtained from [16] given M-ary quadrature amplitude modulation and target bit error rate (BER). N_0 is the background channel noise, which can be calculated by multiplying the bandwidth B and the background noise spectrum density n_0. $I_{j,s,k}^{i,(D)}$ represents the interference term of kth UE in eNB i on the subchannel s of the CC j in data region and can be written as the right hand side of (2.11), which consists of the numerous inter-cell interferences resulting from other eNBs.

Chapter 3

Proposed Joint Component Carrier Selection and Power Allocation (JCP) and Simplified JCP (JCP-S) Schemes

3.1 Geometric Programming and Problem Reformulation

As presented in equations (2.4)-(2.9), exhaustively searching for every possible channel allocations and then finding the best power allocation among them is the most intuitive way to solve this problem, but almost cannot be realized because of unbelievably large computations. From the perspective of computational complexity theory, NP problem is defined as that it can be solved in non-deterministic polynomial time by using an infinite number of calculators. In other words, with finite number of calculators, a NP problem has much higher complexity than polynomial time and is difficult to solved.

Observing our optimization problem and in order to find the global optimum solution, the optimization problem is NP-hard whose complexity is at least as hard as the hardest problems in the NP problem.

With regard to the optimization problem, the problem contains two main kinds of variables to be solved. One is the power set $\mathbf{P}$ that belongs to continuous-type variable and the complete optimization theorem has been well-developed for this type of variable. The other one is the channel indicator sets that belongs to discrete-type variable, including $\bar{\boldsymbol{\rho}}^{(C)}$ and $\bar{\boldsymbol{\rho}}^{(D)}$ which represent the indicator sets for control region and data region respectively. In the integer programming theory, there exists a series of methods to solve the discrete-type optimization problem. However, when considering the problem including both types of variables, this joint problem will become so complicated and difficult to solved. As a result, a modification to the original optimization problem is proposed owing to the complexity. The modification is that making releases of the discrete-type variables to continuous domain. In other words, the concept is trying to solve the joint problem with all of the variables being on continuous domain, then recover the solution, which are originally discrete-type, back to the discrete domain according to some designed algorithms.

Furthermore, on the aspect of channel allocation in the control region, modulation and coding scheme with noise-resisted modulation like QPSK and lower code efficiency ν is preferable and assumed to be used in this region. As mentioned before, how much resource that one subchannel in the control region can provide for transmitting allocative information of data channels is related to what MCS is used, instead of where the subchannel is located in. That is to say, no matter which component carrier the subchannels are located in, one subchannel in the control region can guarantee to transmit allocative information of $\frac{\zeta}{\nu}$ subchannels in the data region. On account of this reason, another modification is proposed which implies that the amount $\sum_{j=1}^{J}\sum_{s=1}^{R}\bar{\rho}_{j,s,k}^{i,(C)}$, which represented how much amount of subchannels are allocated for the control resource of kth UE in eNB i, is the term truely cared about in the allocation problem.

With the modifications mentioned above, the optimization problem can be reformulated as follows

$$\max_{\boldsymbol{\pi},\boldsymbol{\rho}^{(D)},\mathbf{P}} \quad \sum_{i=1}^{M}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{s=1}^{R} C_{j,s,k}^{i,(D)} \tag{3.1}$$

subject to:

$$\pi_k^i \in [0,1]\,, \rho_{j,s,k}^{i,(D)} \in [0,1]\,, \qquad \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K} \tag{3.2}$$

$$\sum_{k=1}^{K} \pi_k^i \le J, \qquad \forall i \in \mathbf{M} \tag{3.3}$$

$$\sum_{k=1}^{K} \rho_{j,s,k}^{i,(D)} \le 1, \qquad \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S} \tag{3.4}$$

$$\sum_{j=1}^{J}\sum_{s=1}^{R}\sum_{k=1}^{K} P_{j,s,k}^{i} \le P_{max}, \qquad \forall i \in \mathbf{M} \tag{3.5}$$

$$\sum_{j=1}^{J}\sum_{s=1}^{R} \rho_{j,s,k}^{i,(D)} \le \frac{\zeta \cdot R}{\nu} \cdot \pi_k^i, \qquad \forall i \in \mathbf{M}, \forall k \in \mathbf{K} \tag{3.6}$$

Different to the original optimization problem in equations (2.4)-(2.9), the new indicator set for the resource allocation in control region are represented as $\boldsymbol{\pi}$ and the indicator $\pi_k^i \in \boldsymbol{\pi}, \forall i \in \mathbf{M}, \forall k \in \mathbf{K}$ represents the ratio of the total subchannels' number allocated for the control channels of the kth UE in eNB i to the total subchannels' number in one component carrier, i.e. the new indicator π_k^i represent the term $\frac{\sum_{j=1}^{J}\sum_{s=1}^{R}\rho_{j,s,k}^{i,(C)}}{R}, \forall i \in \mathbf{M}, \forall k \in \mathbf{K}$, where $\boldsymbol{\rho}^{(\boldsymbol{C})} \in [0,1]$ represents the continuous allocation set for control resource.

Moreover, the constraints $\pi_k^i \in [0,1]$ and $\rho_{j,s,k}^{i,(D)} \in [0,1]$ in equation (3.2) represent the releases of discrete-type sets $\bar{\boldsymbol{\rho}}^{(\boldsymbol{C})}$ and $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ to the continuous domain respectively, which are both in the closed interval between 0 and 1. The constraint in equation (3.3) represents that the total resources selected for control channels by all UEs in one eNB cannot exceed the maximum resources that all J CCs can provide. In addition, there exists some same concepts in the constraints between the origin and the reformulated problems. For example, responding to the constraint in equation (2.6), $\pi_k^i \in [0,1]$ implies that each UE cannot select more than one CC as its control CC, i.e. PCC. Likewise, the concepts of the constraints in equations (3.4) and (3.6) also respond to the constraints of equations (2.7) and (2.9) respectively. Similar to the original optimization problem, the transmission rates on data channel $C_{j,s,k}^{i,(D)}$ in equation (3.1) and the SINR term can both be written as the same forms in equation (2.10) and (2.11) with continuous variables, respectively.

As known in the optimization theory, if a function's Hessian matrix, whose elements are constructed by the second partial derivatives of the function with respect to two variables, is a positive semi-definite matrix, then the function is proven to have convex property. And if an optimization problem has convex property, the global optimal solution can be obtained by using some well-developed methods, like Lagrange method. Unfortunately, observing the reformulated problem, the optimization problem has no convex property mainly due to the consideration of inter-cell interferences. Thus, the geometric programming [17] is utilized whose concept is to transform an original non-convex problem into a convex formulation by introducing some alternative variables and approximations. In our problem, the following lower bound,

$$\mu \log S_0 + \lambda \leq \log (1 + S_0) \tag{3.7}$$

which is tight at S_0 when the approximation parameters are chosen as

$$\mu = \frac{S_0}{1 + S_0} \tag{3.8}$$

$$\lambda = \log(1 + S_0) - \frac{S_0}{1 + S_0} \log S_0 \tag{3.9}$$

is used to substitute for the original channel capacity equation. Therefore, the equation (2.10) can be reformulated as

$$\hat{C}_{j,s,k}^{i,(D)} = \frac{2N_s - N_c}{2N_s} \cdot B \cdot \left(\mu_{j,s,k}^{i} \log_2 S_{j,s,k}^{i,(D)} + \lambda_{j,s,k}^{i} \right) \tag{3.10}$$

where $\mu_{j,s,k}^{i}$ and $\lambda_{j,s,k}^{i}$ are fixed parameters. Define $\mu_{j,s,k}^{i} \log_2 S_{j,s,k}^{i,(D)} + \lambda_{j,s,k}^{i}$ in equation (3.10) as the lower bound term, denoted as $L_{j,s,k}^{i,(D)}$. Since $\hat{C}_{j,s,k}^{i,(D)}$ can be viewed as the lower bound of $C_{j,s,k}^{i,(D)}$ in equation (2.10), the original optimization problem is then transformed to maximize the lower bound of total transmission rates on all data channels, in other words, try to solve the optimization problem from the viewpoint of lower bound. However, (3.10) is still non-convex which requires additional processing to such that it can be transformed into a convex function. Lemma 1 is presented as follows to conduct this transformation.

Lemma 1: The lower bound transmission rate (3.10) can be concavified by the variable transformations: $\hat{P}_{j,s,k}^{i} = \ln(P_{j,s,k}^{i})$ and $\hat{\rho}_{j,s,k}^{i,(D)} = \ln(\rho_{j,s,k}^{i,(D)})$.

Proof: With $P_{j,s,k}^{i} = \exp(\hat{P}_{j,s,k}^{i})$ and $\rho_{j,s,k}^{i,(D)} = \exp(\hat{\rho}_{j,s,k}^{i,(D)})$, the lower bound term $L_{j,s,k}^{i,(D)}$ in (3.10) can be rewritten as

$$\hat{L}_{j,s,k}^{i,(D)} = \frac{\mu_{j,s,k}^{i}}{\ln 2} \left[\epsilon + \hat{\rho}_{j,s,k}^{i,(D)} + \hat{P}_{j,s,k}^{i} - \ln(\hat{I}_{j,s,k}^{i,(D)} + N_0) \right] + \lambda_{j,s,k}^{i} \tag{3.11}$$

where $\epsilon = \ln g_{j,s,k}^{i,i} - \ln \Gamma$.

And the interference term $\hat{I}_{j,s,k}^{i,(D)} = \sum_{q \neq i} \sum_{z=1}^{K} e^{(\hat{\rho}_{j,s,z}^{q,(D)} + \hat{P}_{j,s,k}^{q})} \cdot g_{j,s,k}^{q,i}$. Observing (3.11), we can find that this function is constructed by a linear function plus a *log-sum-exp* function $\ln(\hat{I}_{j,s,k}^{i,(D)} + N_0)$, which is proven to be convex in [18]. Thus, the reformulated lower bound term is a concave function.

After the lower bound and variable transformations, the objective function of the GP optimization problem can be written as

$$\max_{\boldsymbol{\pi}, \hat{\boldsymbol{\rho}}^{(\boldsymbol{D})}, \hat{\boldsymbol{P}}} \quad \sum_{i=1}^{M} \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{s=1}^{R} \check{C}_{j,s,k}^{i,(D)} \tag{3.12}$$

where

$$\check{C}_{j,s,k}^{i,(D)} = \hat{C}_{j,s,k}^{i,(D)}(e^{\hat{\boldsymbol{P}}}, e^{\hat{\boldsymbol{\rho}}^{(\boldsymbol{D})}}) \tag{3.13}$$

And the new constraints can all be obtained from the constraints in equation (3.2)-(3.6) with $\boldsymbol{\rho}^{(\boldsymbol{D})}$ and $\mathbf{P}$ replaced by $e^{\hat{\boldsymbol{\rho}}^{(\boldsymbol{D})}}$ and $e^{\hat{\boldsymbol{P}}}$ respectively.

3.2 Algorithms for JCP Scheme

After the GP transformation, find that the objective function of the optimization problem is a concave function and all of the constraints are linear functions. Therefore, the global optimal solutions of the control channel's allocation $\boldsymbol{\pi}$, the data channel's allocation $\hat{\boldsymbol{\rho}}^{(\boldsymbol{D})}$, and the power allocation $\hat{\boldsymbol{P}}$ can all be jointly solved in continuous domain by the well-developed numerical analysis's optimization method. The detailed processes to jointly solve these three kinds of variables in the JCP scheme are given in **Algorithm 1**. In the iterative progress of this algorithm, once the optimal solutions are acquired, the solutions that had been transformed into new domains should be transferred back to the original domain. For example, the solutions of the power in new domain $\hat{\boldsymbol{P}}$ should be transformed back to the original domain $\boldsymbol{P}$ by $P_{j,s,k}^{i} = \exp(\hat{P}_{j,s,k}^{i})$.

The three kinds of solutions can be obtained from the output of **Algorithm 1**. However, observing these solutions, all of them are continuous and some of them are not matched to the original domain defined in section 2.2 since the releases of variables from discrete domain to the continuous domain. For instance, consider the constraints in equations (2.5)-(2.7) and the definition of variable set $\boldsymbol{\pi}$. Each continuous control channel's allocation

Algorithm 1: JCP scheme for joint channel and power allocation

Input: $\boldsymbol{g}$

Output: $\boldsymbol{P}, \boldsymbol{\pi}, \boldsymbol{\rho^{(D)}}$

Initialize all $\mu^i_{j,s,k,(0)}$ and $\lambda^i_{j,s,k,(0)}$ according to (3.8)-(3.9) given a initial SINR S_0

Initialize counter of iteration $n = 0$

repeat

  Maximize: after lower bound and variable transformation, solve the optimization problem (3.12) and transform the solutions back to the original formulation with $P^i_{j,s,k,(n)} = \exp(\hat{P}^i_{j,s,k,(n)})$ and $\rho^{i,(D)}_{j,s,k,(n)} = \exp(\hat{\rho}^{i,(D)}_{j,s,k,(n)}), \forall i, \forall j, \forall s, \forall k$

  Tighten : update $\mu^i_{j,s,k,(n+1)}$,$\lambda^i_{j,s,k,(n+1)}, \forall i, \forall j, \forall s, \forall k$ according to the new SINR S_{n+1} calculated from $\boldsymbol{P_{(n)}}$ and $\boldsymbol{\rho^{(D)}_{(n)}}$, and then increase n by one

until $\mu^i_{j,s,k,(n+1)}$,$\lambda^i_{j,s,k,(n+1)}, \forall i, \forall j, \forall s, \forall k$ converge

π^i_k is expected to be an integral multiple of $\frac{1}{R}$ because the basic allocative unit in the control region is one subchannel. And the subchannels selected as control channels for an UE can only be located in the same component carrier owing to the constraint in equation (2.6) that regulates an UE can select only one CC as its control CC, i.e. PCC. Moreover, the constraint in equation (2.7) also stipulates that one subchannel can be allocated to one UE for one eNB simultaneously.

For the constraints mentioned above, a heuristic method, called control resource quantization (CRQ) , is proposed to perform the progress about recovering the solution set $\boldsymbol{\pi}$, which is the global optimal solution from the released viewpoint of continuous domain, back to the originally discrete domain set $\bar{\boldsymbol{\pi}}$, and the concept of this method is trying to recover with least shift. In addition, if kth UE in eNB i is allocated with much control resource, i.e. higher π^i_k, it implies that this UE may have better average channel quality so that the performance of total data rate can be enhanced more when allocating more control resource to this UE, where the quantity of control resource influences the maximum number of data channels an UE can use as mentioned before. Consequently, in CRQ method, each eNB has a sequence, which determines the order of selecting control resource for all UEs belonging to this eNB, and the sequence order of kth UE in eNB i is decided by the values of π_k^i. In other words, comparing to the other UEs in the same eNB i, the higher the kth UE's π_k^i is, the earlier this UE can select control resource. After deciding the selecting sequence of each eNB, all UEs of each eNB will follow the sequence to select control resource and recover $\boldsymbol{\pi}$ to discrete domain with least shift. For example, assume the total number of CCs is $J = 3$, the total number of subchannels in one CC is $R = 5$, the total number of UEs in eNB i is $K = 5$, and the allocation for control resource, π_k^i obtained from the output of **Algorithm 1** for each kth UE in eNB i, is given by the table listed in Fig. 3.1. For the first three UEs in the sequence, owing to the existence of unoccupied CCs, each of these UEs can directly transform the π_k^i to discrete domain with least shift and use the corresponding amount of subchannels for control resource in the unoccupied CC. Taking 2th UE in eNB i as an instance, this UE transforms the $\pi_2^i = 0.74$ to discrete $\bar{\pi}_2^i = \frac{4}{R} = 0.8$ and uses corresponding 4 subchannels (SCs) in unoccupied CC2, not to $\frac{3}{R} = 0.6$ because 0.74 is nearer to 0.8 than to 0.6. Then, for the last two UEs, the concept of least shift is still worked. Taking 1th UE in eNB i as the example, there are two CCs, which are CC1 and CC2 respectively, with one SC available, and CC3 has 2SCs available. This UE transforms the $\pi_1^i = 0.48$ to discrete $\bar{\pi}_1^i = \frac{2}{R} = 0.4$ with least shift. In other words, this UE uses 2SCs in CC3 and not use CC1 or CC2 because 0.48 is nearer to 0.4 than to $\frac{1}{R} = 0.2$. Finally, after finishing the allocating process according to selecting sequence, there are probably some SCs not being allocated. In this case, this kind of SCs in each CC is preferable to allocated to the UE, which selects the corresponding CC as control CC and has the highest value of $\bar{\pi}$.

After the determination of discrete allocation for control resource in CRQ, the continuous allocation for data channel $\boldsymbol{\rho}^{(\boldsymbol{D})}$ obtained from **Algorithm 1** also should be recovered to the discrete domain $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ which belongs to the value 0 or 1. However, on account of that the optimal solution of $\boldsymbol{\rho^{(D)}}$ and $\boldsymbol{P}$ are jointly calculated with the released allocation $\boldsymbol{\pi}$, the solution of allocation for data channel and power are supposed to be calculated again in the optimization problem where the allocation for control resource is known as constant and discrete value $\bar{\boldsymbol{\pi}}$ that had been decided in CRQ. In other words, the more precise $\tilde{\boldsymbol{\rho}}^{\boldsymbol{(D)}}$ and $\tilde{\boldsymbol{P}}$ are expected to be solved in the GP optimization problem with $\bar{\boldsymbol{\pi}}$ being known. Once the refined solutions $\tilde{\boldsymbol{\rho}}^{\boldsymbol{(D)}}$ and $\tilde{\boldsymbol{P}}$ are calculated, another method, called data resource quantization (DRQ), is proposed to recover the allocation for data channel, $\tilde{\boldsymbol{\rho}}^{\boldsymbol{(D)}}$, to discrete domain.

With reference to the $\tilde{\boldsymbol{\rho}}^{\boldsymbol{(D)}}$ and $\tilde{\boldsymbol{P}}$, all UEs in each eNB can calculate their own equivalent capacity $\tilde{\boldsymbol{C}}$ on each subchannel and the proposed DRQ method can utilize this equivalent capacity to allocate data resource. The equivalent capacity of the kth UE in eNB i on subcarriers s in CC j can be calculated as follows

$$\tilde{C}^{i,(D)}_{j,s,k} = \frac{2N_s - N_c}{2N_s} \cdot B \cdot \log_2(1 + \frac{\tilde{\rho}^{i,(D)}_{j,s,k} \cdot \tilde{P}^{i}_{j,s,k} \cdot g^{i,i}_{j,s,k}}{\Gamma \cdot (N_0 + \sum_{q \neq i} \sum_{z=1}^{K} \tilde{\rho}^{q,(D)}_{j,s,z} \cdot \tilde{P}^{q}_{j,s,k} \cdot g^{q,i}_{j,s,k})}) \quad (3.14)$$

Considering the constraint that one subchannel can allocate to at most one UE for an eNB for the sake of avoiding intra-cell interference, each eNB is preferable to allocate resource to the UE, who has the highest equivalent capacity. Besides, in the course of allocation, each eNB should keep an eye on the total amount of control resource that each UE obtains. In other words, eNB i would allocate the subchannel s in CC j to its kth UE, who has the highest equivalent capacity comparing with the other UEs and still has available control resource which is used to transmit the additional allocative information of subchannel s. The detailed processes of transforming continuous solutions to discrete domains in JCP scheme are given in **Algorithm 2** and **Algorithm 3** respectively.

Completing three algorithms mentioned above, two kinds of discrete so-

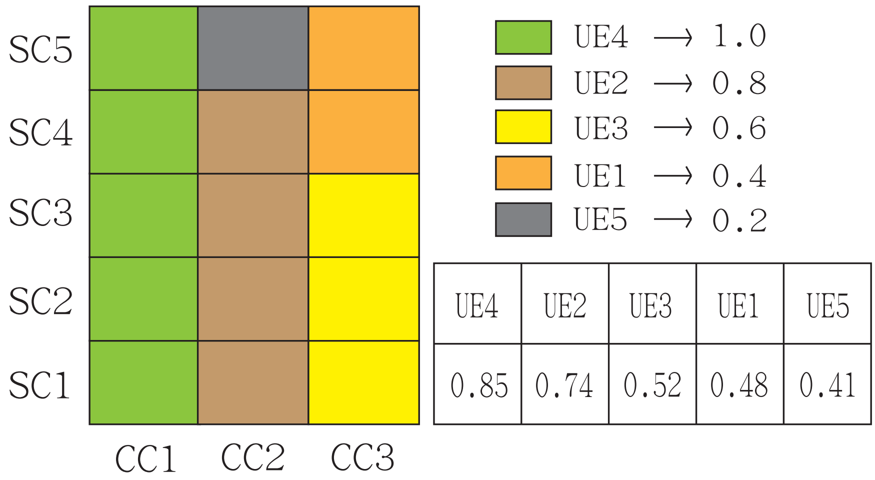

Figure 3.1: Example of sequence order and allocation for control resource.

lution have been solved, which are the allocation for control resource, $\bar{\boldsymbol{\pi}}$, and for data resource, $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$, respectively. In the final step of JCP scheme, the final power allocation can be calculated in the GP optimization problem with all allocations for channel resource being known. Summarily, the whole process for JCP scheme can be shown as Fig. 3.2.

3.3 Problem Reformulation in JCP-S Scheme

Although the existence of undeterministic inter-cell interference is a realistic consideration in the optimization problem formed in previous chapters, the computational complexity and difficulty in mathematical analysis would also get much higher under this consideration. Consequently, an assumption is introduced to JCP-S scheme, which assumes that inter-cell interference term is a constant value in the optimization process. The reformulated optimization problem in JCP-S is shown as follows

$$\max_{\boldsymbol{\rho}^{(D)},\mathbf{P}} \quad \sum_{i=1}^{M}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{s=1}^{R} C_{j,s,k}^{i,(D)} \tag{3.15}$$

Algorithm 2: Control resource quantization (CRQ)

```
Input: π, g
Output: π̄
begin
    1. Sort π to form the selecting sequence for each eNB:
    Initial π_0^i = −1, ∀i ∈ M and S(1 : N, 1 : K) = 0
    for n = 1 to N do
        for k = 1 to K do
            for o = 1 to K do
                if π_k^n > π_{S(n,o)}^n then
                    o_t = o break
            S_pre = S and S(n, o_t) = k
            for ô = o_t to K do
                if S_pre(n, ô) ≠ 0 then
                    S(n, ô + 1) = S_pre(n, ô)
    2. Recover continuous π to discrete π̄:
    Initial π̄ = −1 and A(1 : N, 1 : J) = 1
    for n = 1 to N do
        for o = 1 to K do
            for j = 1 to J do
                if A(n, j) ≥ π_{S(n,o)}^n then
                    u* = arg min(u/R − π_{S(n,o)}^n)^2,    u ∈ {0, 1, .., R}
                    π̄_{S(n,o)}^n = u*/R , A(n, j) = A(n, j) − π̄_{S(n,o)}^n break
            if π̄_{S(n,o)}^n = −1 then
                j* = arg min(π_{S(n,o)}^n − A(n, j))^2,    j ∈ {0, 1, .., J}
                π̄_{S(n,o)}^n = A(n, j*) , A(n, j*) = 0 break
    for n = 1 to N do
        if J ≤ K then
            for j = 1 to J do
                π̄_{S(n,j)}^n = π̄_{S(n,j)}^n + A(n, j)
        else
            for j = 1 to K do
                π̄_{S(n,j)}^n = 1
```

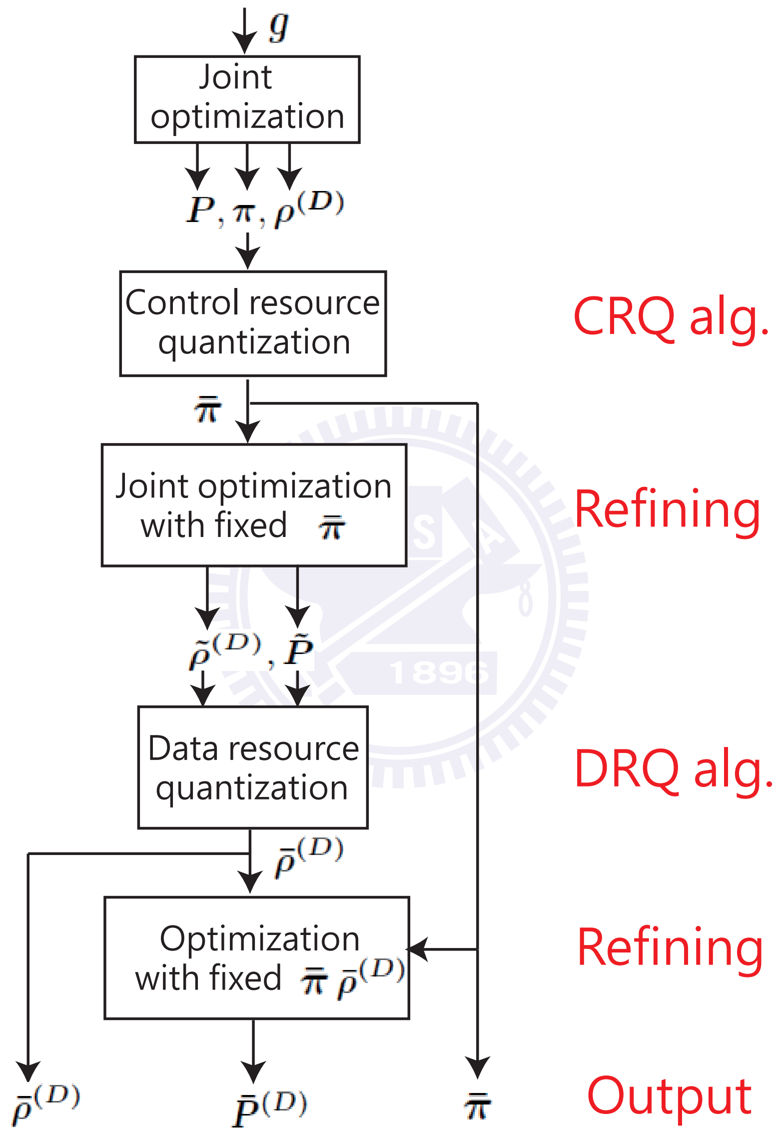

Figure 3.2: Whole process for JCP scheme.

Algorithm 3: Data resource quantization (DRQ)

Input: $\bar{\boldsymbol{\pi}}, \tilde{\boldsymbol{\rho}}^{(\boldsymbol{D})}, \tilde{\boldsymbol{P}}, \boldsymbol{g}$
Output: $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$
begin
  1. Recover continuous $\tilde{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ to discrete $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$:
  Initial $\boldsymbol{K_i} \in$ the set of all UEs in eNB i, $\quad \forall i \in \mathbf{M}$
  Initial $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})} = 0$
  for $j = 1$ *to* J **do**
    for $s = 1$ *to* R **do**
      for $n = 1$ *to* N **do**
        for $k = 1$ *to* K **do**
          $\tilde{C}^{n,(D)}_{j,s,k}$=equation (3.14)
        $u^* = \arg\max \tilde{C}^{n,(D)}_{j,s,u}, \quad u \in \boldsymbol{K_n}$
        $\bar{\rho}^{n,(D)}_{j,s,u^*} = 1$ and $\bar{\rho}^{n,(D)}_{j,s,u} = 0, \quad u \notin u^*$
        if $\sum_{\hat{j}=1}^{J} \sum_{\hat{s}=1}^{R} \bar{\rho}^{n,(D)}_{\hat{j},\hat{s},u^*} = \lfloor \frac{\zeta \cdot R}{\nu} \cdot \bar{\pi}^{n}_{u^*} \rfloor$ **then**
          $\boldsymbol{K_n} = \boldsymbol{K_n} - \{u^*\}$

subject to:

$$\rho^{i,(D)}_{j,s,k} \in [0,1], \qquad \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K} \tag{3.16}$$

$$\sum_{k=1}^{K} \rho^{i,(D)}_{j,s,k} \leq 1, \qquad \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S} \tag{3.17}$$

$$\sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{s=1}^{R} P^{i}_{j,s,k} \leq P_{max}, \qquad \forall i \in \mathbf{M} \tag{3.18}$$

where

$$C^{i,(D)}_{j,s,k} = \frac{2N_s - N_c}{2N_s} \cdot B \cdot \rho^{i,(D)}_{j,s,k} \cdot \log_2(1 + \frac{P^{i}_{j,s,k} \cdot g^{i,i}_{j,s,k}}{\Gamma \cdot (N_0 + I_c)}) = \frac{2N_s - N_c}{2N_s} \cdot B \cdot \rho^{i,(D)}_{j,s,k} \cdot f(P^{i}_{j,s,k}) \tag{3.19}$$

The I_c is the constant interference term. Observing from the problem above, the allocation for control resource $\boldsymbol{\pi}$ isn't considered in the optimization of JCP-S scheme and is supposed to be considered later. However, even though the logarithm function $f(P^{i}_{j,s,k})$ is concave in $P^{i}_{j,s,k}$, the integrated function $\rho_{j,s,k}^{i,(D)} \cdot f(P_{j,s,k}^i)$ is not concave in $(\rho_{j,s,k}^{i,(D)}, P_{j,s,k}^i)$. Hence, a variable transformation $\varepsilon_{j,s,k}^i = P_{j,s,k}^i \cdot \rho_{j,s,k}^{i,(D)}$ is also utilized to concavify the problem and rewrite the integrated function as $\rho_{j,s,k}^{i,(D)} \cdot f(\frac{\varepsilon_{j,s,k}^i}{\rho_{j,s,k}^{i,(D)}})$, which is proven to be a concave function in $(\varepsilon_{j,s,k}^i, \rho_{j,s,k}^{i,(D)})$. And the new variable set $\boldsymbol{\varepsilon}$ can be view as the effective transmission power. With the variable transformation, the channel capacity (3.19) can be rewritten as

$$C_{j,s,k}^{i,(D)} = \frac{2N_s - N_c}{2N_s} \cdot B \cdot \rho_{j,s,k}^{i,(D)} \cdot \log_2(1 + \frac{\varepsilon_{j,s,k}^i \cdot g_{j,s,k}^{i,i}}{\rho_{j,s,k}^{i,(D)} \cdot \Gamma \cdot (N_0 + I_c)}) \tag{3.20}$$

and the constraint in equation (3.18) can also be rewritten as

$$\sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{s=1}^{R} \varepsilon_{j,s,k}^i \leq P_{max}, \quad \forall i \in \mathbf{M} \tag{3.21}$$

Then, the optimization problem is reformulated as a concave maximization problem. Besides, in the process of concavifying, the value 1 in the formula of channel capacity, $\log_2(1 + S)$, doesn't require to be canceled, which has been canceled in JCP scheme in order to concavify the optimization problem under the consideration of undeterministic interference. Note that if the number 1 has been canceled, the logarithmic function will equal to a negative value with the SINR $S < 1$ and to a much negative value with the SINR $S \ll 1$. For this reason, except for the determinism for interference term, JCP-S scheme has good approximation in low SINR environment.

3.4 Proposed JCP-S Scheme

In this section, the proposed JCP-S scheme will be designed to allocate subchannel in both regions and transmission power in order to maximize the total data rate of the entire system. According to optimization theorem, let $\boldsymbol{\beta}, \boldsymbol{\eta}, \boldsymbol{\Phi}$ and $\boldsymbol{\theta}$ be the Lagrangian multiplier sets for the constraints in (3.16), (3.17), and (3.21) respectively. In addition, $\boldsymbol{\Lambda}$ is defined as the set of all

Lagrangian multipliers. Then, the Lagrangian function $L(\boldsymbol{\rho}^{(\boldsymbol{D})}, \mathbf{P}, \boldsymbol{\Lambda})$ of the previous reformulated concave optimization problem can be shown as follows

$$
\begin{aligned}
L(\boldsymbol{\rho}^{(\boldsymbol{D})}, \mathbf{P}, \boldsymbol{\Lambda}) &= \sum_{i=1}^{M}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{s=1}^{R} C_{j,s,k}^{i,(D)} + \sum_{i=1}^{M}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{s=1}^{R} \beta_{j,s,k}^{i}(\rho_{j,s,k}^{i,(D)}) \\
&- \sum_{i=1}^{M}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{s=1}^{R} \eta_{j,s,k}^{i}(\rho_{j,s,k}^{i,(D)} - 1) - \sum_{i=1}^{M}\sum_{j=1}^{J}\sum_{s=1}^{R} \Phi_{j,s}^{i}(\sum_{k=1}^{K} \rho_{j,s,k}^{i,(D)} - 1) \\
&- \sum_{i=1}^{M} \theta_i(\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{s=1}^{R} \varepsilon_{j,s,k}^{i} - P_{max})
\end{aligned} \tag{3.22}
$$

After that, the Karush-Kuhn-Tucker (KKT) conditions for deriving the optimal solution are

$$
\frac{\partial L(\boldsymbol{\rho}^{(\boldsymbol{D})}, \mathbf{P}, \boldsymbol{\Lambda})}{\partial \varepsilon_{j,s,k}^{i}} \begin{cases} \geq 0, & \text{if } \varepsilon_{j,s,k}^{i} = 0 \\ = 0, & \text{if } \varepsilon_{j,s,k}^{i} > 0 \end{cases} \tag{3.23}
$$

$$
\frac{\partial L(\boldsymbol{\rho}^{(\boldsymbol{D})}, \mathbf{P}, \boldsymbol{\Lambda})}{\partial \rho_{j,s,k}^{i,(D)}} \begin{cases} \geq 0, & \text{if } \rho_{j,s,k}^{i,(D)} = 0 \\ = 0, & \text{if } \rho_{j,s,k}^{i,(D)} > 0 \end{cases} \tag{3.24}
$$

The partial derivative of Lagrangian function with respect to $\varepsilon_{j,s,k}^{i}$ can further be expressed as

$$
\frac{\partial L(\boldsymbol{\rho}^{(\boldsymbol{D})}, \mathbf{P}, \boldsymbol{\Lambda})}{\partial \varepsilon_{j,s,k}^{i}} = \frac{B \rho_{j,s,k}^{i,(D)} g_{j,s,k}^{i,i}}{\ln 2[\rho_{j,s,k}^{i,(D)}(N_0 + I_c) + \varepsilon_{j,s,k}^{i} g_{j,s,k}^{i,i}]} \tag{3.25}
$$

Consequently, according to equations (3.23) and (3.25), the effective transmission power $\varepsilon_{j,s,k}^{i}$ can be derived as

$$
\varepsilon_{j,s,k}^{i} = \rho_{j,s,k}^{i,(D)}[\frac{B}{\theta_i \ln 2} - \frac{(N_0 + I_c)}{g_{j,s,k}^{i,i}}]^{+} \tag{3.26}
$$

where the expression $[z]^{+}$ in equation (3.26) indicates that $[z]^{+} = z$ if $z \geq 0$ and $[z]^{+} = 0$ if $z < 0$. The term $\frac{B}{\theta_i \ln 2}$ can be viewed as the concept of conventional water level. Similarly, the partial derivative of Lagrangian function with respect to $\rho^{i,(D)}_{j,s,k}$ can be derived as

$$\frac{\partial L(\boldsymbol{\rho}^{(\boldsymbol{D})}, \mathbf{P}, \boldsymbol{\Lambda})}{\partial \rho^{i,(D)}_{j,s,k}} =$$

$$-\eta^i_{j,s,k} + \beta^i_{j,s,k} - \Phi^i_{j,s} + \frac{B}{\ln 2}[\ln(1 + \frac{\varepsilon^i_{j,s,k} g^{i,i}_{j,s,k}}{\rho^{i,(D)}_{j,s,k}(N_0 + I_c)}) - \frac{\varepsilon^i_{j,s,k} g^{i,i}_{j,s,k}}{\rho^{i,(D)}_{j,s,k}(N_0 + I_c) + \varepsilon^i_{j,s,k} g^{i,i}_{j,s,k}}] \tag{3.27}$$

By replacing the result in equation (3.26) into equation (3.27), the function $R^i_{j,s,k}$ can be defined as effect capacity and written as follows

$$\begin{aligned} R^i_{j,s,k} &= \frac{B}{\ln 2}[\ln(1 + \frac{\varepsilon^i_{j,s,k} g^{i,i}_{j,s,k}}{\rho^{i,(D)}_{j,s,k}(N_0 + I_c)}) - \frac{\varepsilon^i_{j,s,k} g^{i,i}_{j,s,k}}{\rho^{i,(D)}_{j,s,k}(N_0 + I_c) + \varepsilon^i_{j,s,k} g^{i,i}_{j,s,k}}] \\ &= \frac{B}{\ln 2}\{[\ln(\frac{B g^{i,i}_{j,s,k}}{\theta_i \ln 2(N_0 + I_c)})]^+ - [1 - \frac{(N_0 + I_c)\theta_i \ln 2}{B g^{i,i}_{j,s,k} - \theta_i \ln 2(N_0 + I_c - 1)}]^+\} \end{aligned} \tag{3.28}$$

And from equation (3.24), the result below can be inferred

$$R^i_{j,s,k} \begin{cases} \leq \eta^i_{j,s,k} - \beta^i_{j,s,k} + \Phi^i_{j,s}, & \text{if } \rho^{i,(D)}_{j,s,k} = 0 \\ = \eta^i_{j,s,k} - \beta^i_{j,s,k} + \Phi^i_{j,s}, & \text{if } \rho^{i,(D)}_{j,s,k} > 0 \end{cases} \tag{3.29}$$

Thus, solve the simultaneous equations containing equations (3.26) and (3.29). We can get the continuous solution sets $\boldsymbol{\rho}^{(D)}$ and $\boldsymbol{\varepsilon}$.

Furthermore, for the sake of obtaining the continuous solution sets $\boldsymbol{\rho}^{(\boldsymbol{D})}$ and $\boldsymbol{\varepsilon}$ from the simultaneous equations containing equations (3.26) and (3.29), the values of Lagrangian multipliers are required to be solved. Another iterative approach that use the subgradient method as in [19] is utilized to update the value of Lagrangian multipliers. Thus, the Lagrangian multiplier sets $\boldsymbol{\beta}, \boldsymbol{\eta}, \boldsymbol{\Phi}$ and $\boldsymbol{\theta}$ can be calculated by the following updated equations.

$$\begin{aligned}
\beta_{j,s,k}^{i,(n+1)} &= [\beta_{j,s,k}^{i,(n)} + s^{(n)}(\rho_{j,s,k}^{i,(D)})]^+ \\
\eta_{j,s,k}^{i,(n+1)} &= [\eta_{j,s,k}^{i,(n)} - s^{(n)}(\rho_{j,s,k}^{i,(D)} - 1)]^+ \\
\Phi_{j,s}^{i,(n+1)} &= [\Phi_{j,s}^{i,(n)} - s^{(n)}(\sum_{k=1}^{K} \rho_{j,s,k}^{i,(D)} - 1)]^+ \\
\theta_i^{(n+1)} &= [\theta_i^{(n)} - s^{(n)}(\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{s=1}^{R} \varepsilon_{j,s,k}^{i} - P_{max})]^+
\end{aligned} \tag{3.30}$$

where $\beta_{j,s,k}^{i,(n)}, \eta_{j,s,k}^{i,(n)}, \Phi_{j,s}^{i,(n)}$ and $\theta_i^{(n)}$ represent the n th iteration of the Lagrangian multipliers $\beta_{j,s,k}^{i}, \eta_{j,s,k}^{i}, \Phi_{j,s}^{i}$ and θ_i respectively. Beside, $s^{(n)} = \frac{\chi}{\sqrt{n}}$ is the step size and χ is a tunable constant.

However, considering the solution set $\boldsymbol{\rho}^{(D)}$ belonging to continuous domain and the constraint that each subchannel can be allocated to at most one UE for an eNB, the following proposition can be proposed

Proposition 1. *(Necessary condition for exclusively optimal channel assignment):* **Assuming $\rho_{j,s,k}^{i,(D)}, \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K}$ is the optimal subchannel allocation for problem in equations (3.15)-(3.17) and (3.21), if subchannel $\hat{s}$ on CC $\hat{j}$ is exclusively allocated to $\hat{k}$th UE in eNB $\hat{n}$, i.e. $\rho_{\hat{j},\hat{s},\hat{k}}^{\hat{n},(D)} = 1$ and $\rho_{\hat{j},\hat{s},k}^{\hat{n},(D)} = 0, \forall k \neq \hat{k}$, then it should satisfy:**

$$R_{\hat{j},\hat{s},\hat{k}}^{\hat{n}} > R_{\hat{j},\hat{s},k}^{\hat{n}} \quad , \quad \forall k \neq \hat{k} \tag{3.31}$$

and implies that:

$$\hat{k} = \arg\max_{k} R_{\hat{j},\hat{s},k}^{\hat{n}} \quad , \quad \forall k \in \textit{the set of all UEs in eNB } \hat{n} \tag{3.32}$$

Proof: **The Karush-Kuhn-Tucker conditions are:**

$$\begin{aligned}
&(1) \quad \beta_{j,s,k}^{i}(\rho_{j,s,k}^{i,(D)}) = 0, \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K} \\
&\quad \Rightarrow \textit{so if } \rho_{j,s,k}^{i,(D)} = 0, \textit{ then } \beta_{j,s,k}^{i} > 0, \textit{ else } \beta_{j,s,k}^{i} = 0
\end{aligned} \tag{3.33}$$

$$\begin{aligned}
&(2) \quad \eta_{j,s,k}^{i}(\rho_{j,s,k}^{i,(D)} - 1) = 0, \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K} \\
&\quad \Rightarrow \textit{so if } \rho_{j,s,k}^{i,(D)} = 1, \textit{ then } \eta_{j,s,k}^{i} > 0, \textit{ else } \eta_{j,s,k}^{i} = 0
\end{aligned} \tag{3.34}$$

According to the result in equation (3.29) and the conditions above, if

subchannel $\hat{s}$ on CC $\hat{j}$ is exclusively allocated to $\hat{k}$th UE in eNB $\hat{n}$, i.e. $\rho^{\hat{n},(D)}_{\hat{j},\hat{s},\hat{k}} = 1$ and $\rho^{\hat{n},(D)}_{\hat{j},\hat{s},k} = 0, \forall k \neq \hat{k}$, then

$$R^{\hat{n}}_{\hat{j},\hat{s},\hat{k}} - R^{\hat{n}}_{\hat{j},\hat{s},k} \geq (\eta^{\hat{n}}_{\hat{j},\hat{s},\hat{k}} + \Phi^{\hat{n}}_{\hat{j},\hat{s}}) - (-\beta^{\hat{n}}_{\hat{j},\hat{s},k} + \Phi^{\hat{n}}_{\hat{j},\hat{s}}) = \eta^{\hat{n}}_{\hat{j},\hat{s},\hat{k}} + \beta^{\hat{n}}_{\hat{j},\hat{s},k} > 0 \qquad (3.35)$$

In other words, the JCP-S scheme would allocate subchannel s on CC j to the kth UE in eNB n who has the largest $R^{n}_{j,s,k}$ comparing with the other UEs in the same eNB n. However, as mentioned before, the allocation for data channel is released from the original discrete set, i.e. $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})} \in \{0, 1\}$, into the continuous set, i.e. $\boldsymbol{\rho}^{(\boldsymbol{D})} \in [0, 1]$. As a consequence, the result of optimal solution can happen to be situated at the interval $[0, 1]$, i.e. not exclusive concept. In such case, the discrete solution set of allocation for data resource $\hat{\boldsymbol{\rho}}^{(\boldsymbol{D})}$, which is obtained according to **Proposition 1**, is suboptimal not optimal unless the continuous solution set $\boldsymbol{\rho}^{(\boldsymbol{D})}$ belongs to 0 or 1 originally.

With the solutions of each Lagrangian multiplier which is the convergent result in equations (3.30), the suboptimal discrete solution set $\hat{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ can be determined by **Proposition 1**. However, this result doesn't consider the constraint of allocation for control resource. Therefore, an instinct method is proposed to make the allocation be constrained by control resource. In this method, there is a selecting sequence for all UEs in each eNB. And the concept of this sequence is that the more subchannels an UE in one eNB gets, the earlier this UE can occupy control resource. And if the total amount of subchannels $n^{'}$ that one UE gets for data channels exceeds the maximum amount $n^{''}$ that the remaining control resource can guarantee, the total amount of subchannels of this UE is adjusted to this maximum amount $n^{'} \rightarrow n^{''}$ and select the top $n^{''}$ subchannel which is big in value of effective capacity as its updated subchannels for data resource. However, after completing the selecting sequence of one eNB, there are probably subchannels that are not allocated to any UE owing to the prior adjustment. In such case, it prefers to allocate to the UE with largest effective capacity on this subchannel who still has available and remaining control resource can use. After that, the

Algorithm 4: Detailed steps for JCP-S scheme

Input: $\boldsymbol{g}$

Output: $\bar{\boldsymbol{P}}, \bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$

1: Initialize $\beta_{j,s,k}^{(0)}, \eta_{j,s,k}^{(0)}, \Phi_{j,s}^{(0)}$ and $\theta_{(i)}^{(0)}, \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K}$

2: Initialize counter of iteration $n = 0$

3: **repeat**

4: *Calculate :* With the Lagrangian multipliers obtained in iteration n, solve the simultaneous equations containing equations (3.26) and (3.29). And get $\rho_{j,s,k}^{i,(D),(n)}$ and $\varepsilon_{j,s,k}^{i,(n)}, \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K}$

5: *Update :* Obtain $\beta_{j,s,k}^{(n+1)}, \eta_{j,s,k}^{(n+1)}, \Phi_{j,s}^{(n+1)}$ and $\theta_{(i)}^{(n+1)}, \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K}$ according to the updated equations (3.30), and then increase n by one

6: **until** all Lagrangian multipliers converge

7: Obtain the suboptimal allocation for data channel $\hat{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ according to **Proposition 1**

8: Execute the method that makes the allocation $\hat{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ be constrained by control resource, and get final solution for $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$

9: Obtain final power $\bar{\boldsymbol{P}}$ in the optimization problem where the allocation for data channel is known as $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ and the interference term is similarly viewed as constant value

final allocation $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ for data resource can be obtained.

Like the JCP scheme, the final power $\bar{\boldsymbol{P}}$ will be calculated again in the optimization problem where the allocation for data channel is known as $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ and the interference term is similarly viewed as constant value. The **Algorithm 4** shows the detailed steps to get the solution in JCP-S scheme.

Chapter 4

Proposed Heuristic Component Carrier Selection and Power Allocation (HCP) and Simplified HCP (HCP-S) Scheme

4.1 Proposed HCP and HCP-S Schemes

Pondering on the high complexity of the joint problem which considers two kinds of resource allocation at the same time, the HCP and HCP-S scheme prefer to separate this joint problem into two subproblems, which are channel allocation and power allocation respectively. That is to say, the concept of HCP and HCP-S schemes would decide how to allocate data and control channel resource to UEs in the first step. Then, secondly determine how much power should be transmitted on the channels whose allocation have been decided in the first step.

Assume that equal power is used in the first step of HCP and HCP-S schemes. In the first step, each eNB will allocate each subchannel to the adaptive UE for data transmission. In other words, for each subchannel on each CC, each eNB will select one of its UEs, who is the most suitable UE to occupy this subchannel for data channel with the least total interference comparing among the UEs who satisfies two conditions, i.e. **Condition 1** and **Condition 2** respectively. The first condition is that the CC, where this UE's PCC is located in, still has remaining unoccupied control resources for transmitting the allocative information of this additional subchannel, or this UE had never selected PCC. The second condition is that the total transmission rate of the entire system will increase after allocating this subchannel to this UE. The reason of the first condition is to consider the relation between control and data resource as mention before. The reason of the second condition is that if the total data rate of the entire system will not increase after allocating this subchannel to this UE, it means that, even though this UE has the least total interference comparing to the other UEs, this subchannel might be in a saturated state where the negative effect of total interference on total data rate is more than the positive effect of rate improvement. In other words, subchannel resource will be truly allocated to the UE with least interference and these conditions. In addition, if UE had never select PCC for control channel, it will select the most unoccupied CC as PCC owing to having more chance to get subchannel for data transmission. Note that the total interference of one UE contains two sorts. One is the outgoing interference and the other is the incoming interference, which represent the total interference to and from other eNBs respectively. And the background interference matrix (BIM) is to record the outgoing and incoming interference for each UE.

In the second step, the power allocation will be calculated from the optimization problem where the allocation for data channel is known in the first step. Besides, the optimization problem for power allocation can be formulated to GP-form which consider the undeterministic interference term as mentioned in **Section 3.1**, and call it as HCP scheme if the power allocation is obtained from this way. Or can also be formulated to the form where the interference is view as deterministic term as mentioned in **Section 3.3**, and call it as HCP-S scheme. Finally, the detailed steps for HCP and HCP-S schemes are shown in **Algorithm 5**

Algorithm 5: Detailed steps for HCP and HCP-S schemes

Input: $\boldsymbol{g}$
Output: $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}, \bar{\boldsymbol{P}}^{(\boldsymbol{D})}$
begin
  1. Obtain the allocation for data channel $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$:
  Initial $P^i_{j,s,k} = P_{equal}, \forall i \in \mathbf{M}, \forall j \in \mathbf{J}, \forall s \in \mathbf{S}, \forall k \in \mathbf{K}$
  Initial $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})} = 0$
  for $j = 1$ *to* J **do**
    for $s = 1$ *to* R **do**
      for $n = 1$ *to* N **do**
        1. Initial $\hat{k} = 0$
        2. Find the UE $\hat{k}$ with least total interference among the UEs served by eNB n that satisfy **Condition 1** and **Condition 2**
        3. **if** $\hat{k} \neq 0$ **then**
          if *(UE $\hat{k}$ has no PCC)* **then**
            UE $\hat{k}$ selects CC which has the most unoccupied subchannels as PCC
          $\bar{\rho}^{n,(D)}_{j,s,\hat{k}} = 1$

  2. Calculate power allocation $\bar{\boldsymbol{P}}^{(\boldsymbol{D})}$ with fixed $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$:
  With the allocation for data channel $\bar{\boldsymbol{\rho}}^{(\boldsymbol{D})}$ being known, the power allocation $\bar{\boldsymbol{P}}^{(\boldsymbol{D})}$ can be calculated from optimization problem as the form in **Section 3.1** or in **Section 4.1**

Chapter 5

Performance Evaluation

In addition to the proposed JCP, JCP-S, HCP, and HCP-S schemes, the heuristic scheme mentioned above with equal power allocation, which is called HCP-E scheme, is also considered in this thesis for comparison purposes. That is, the power in HCP scheme is allocated equally across all used channels. For simplicity, assume that all UEs are stationary and each UE chose the eNB as serving base station (BS) with highest SINR according to reference signal (RS) in control region. In the simulations, the cell deployments follow the wrap around topology [13] and each cell contains a centering eNB with a number of UEs, who chose this eNB as serving BS, uniformly distributed in the cell coverage.

In this section, the simulations are presented to demonstrate the performance of proposed JCP, JCP-S, HCP, HCP-S, and HCP-E schemes from the perspective of total transmission rate in the data region. The simulation is conducted via MATLAB and utilizes CVX [20] as the tool to solve optimization problem. Moreover, the results are all averaged from 100 simulation runs and the related simulation parameters are listed in Table 5.1.

In order to demonstrate the total data rate of JCP, JCP-S, HCP, HCP-S, and HCP-E schemes under different environments where the total number of CC is changed from 1 to 5, the Fig. 5.1 and Fig. 5.2 show the results in high and low SINR situations respectively. In other words, UEs are intentionally

Table 5.1: Simulation Parameters

Bandwidth of each CC for downlink	1 [MHz]
Modulation parameter (Γ)	$-\ln(5 \cdot 0.01)/1.5$
Noise spectrum density (n_0)	-174 [dBm]
Maximum Power (P_{max})	46 [dBm]
Total subchannels' number in one CC (R)	5
Carrier Frequency	700 [MHz] - 2.5 [GHz]
Path loss model from eNB to UE	$128.1 + 37.6 \log_{10}[dB]$
Shadowing standard deviation	10 [dB]
ISD	500 [m]

located in the central area of each cell in Fig. 5.1, which implies that the average SINR is high in general. On the contrary, UEs are intentionally located in the edge of each cell in Fig. 5.2, which implies that the average SINR is low.

Observing these two figures, the performance of JCP scheme is always best comparing to the other schemes. However, JCP scheme has the highest complexity where the joint problem and undeterministic interference term are both considered in JCP scheme. Moreover, the total data rate of HCP scheme is higher than the total data rate of JCP-S scheme in situation of low SINR, but lower in situation of high SINR. This result implies that the concept of interference reduction in the HCP scheme is dominant enough to the performance in situation of low SINR, and it also makes sense that the effect of interference has a great influence on the throughput of the entire system in low SINR condition. Besides, we can see that the performance of HCP-E scheme, which uses simply equal power allocation for power control, is not much worse than the other schemes in situation of high SINR. This result implies that the effect of power allocation doesn't has great influences on the throughput because it doesn't cause much interference no matter how the power allocation is in situation of high SINR.

According to the specification in [21], there exist a modulation and coding scheme (MCS) to stipulate that what modulation and code efficiency should be used in different conditions of channel quality, i.e. channel quality index

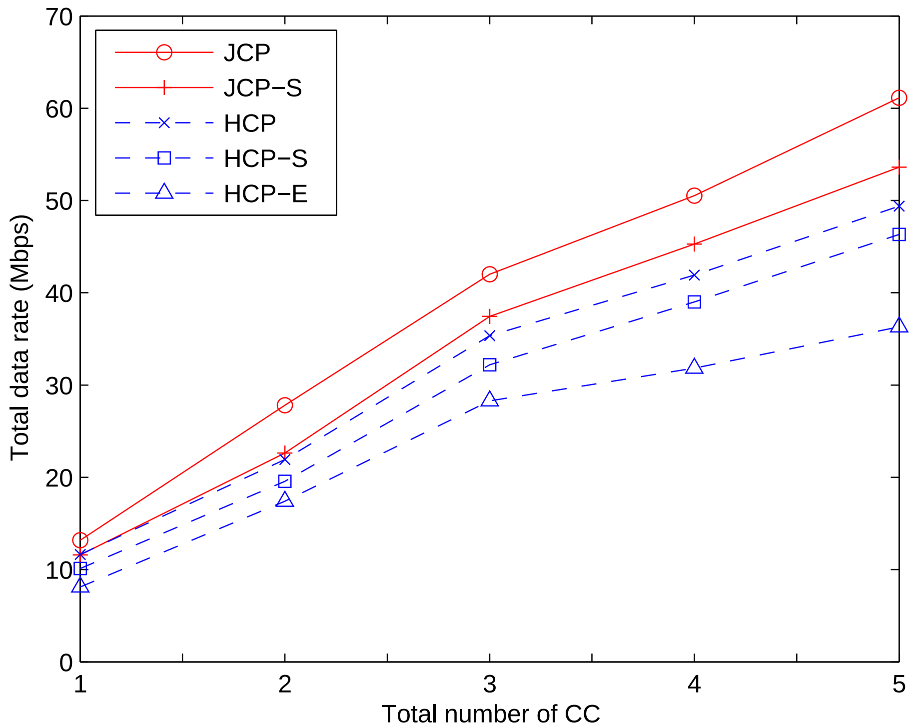

Figure 5.1: Total data rate of JCP, JCP-S, HCP, HCP-S, and HCP-E schemes under different total number of CC, which is changed from 1 to 5, in high SINR situation: total number of eNBs $M = 4$, total number of UEs per eNB $K = 3$, code efficiency $\nu = 0.1523$.

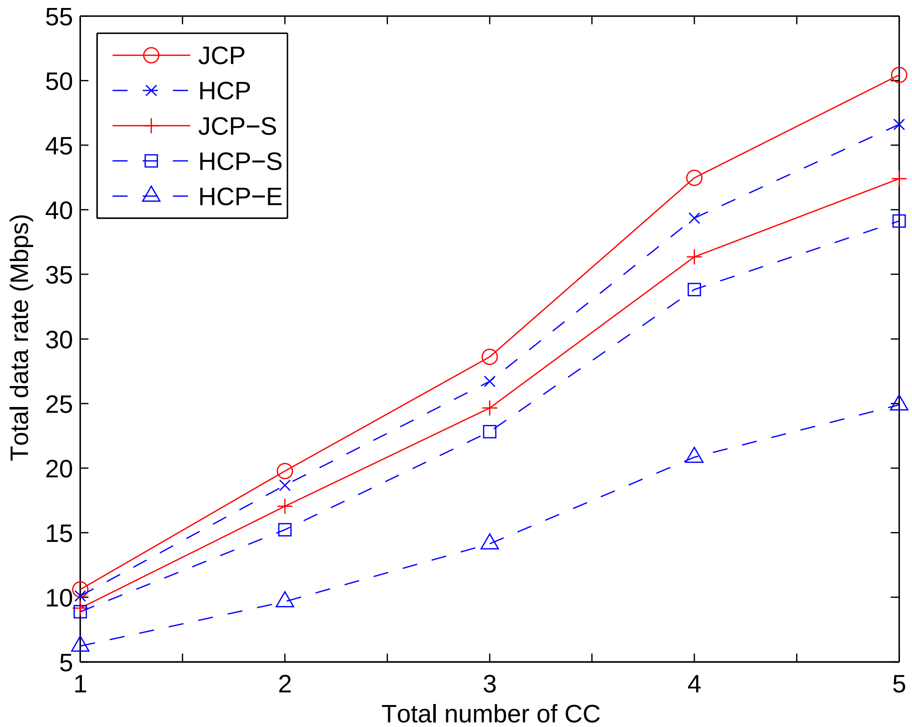

Figure 5.2: Total data rate of JCP, JCP-S, HCP, HCP-S, and HCP-E schemes under different total number of CC, which is changed from 1 to 5, in low SINR situation: total number of eNBs $M = 4$, total number of UEs per eNB $K = 3$, code efficiency $\nu = 0.1523$.

(CQI) in MCS. As mentioned before, what modulation and code efficiency is used influences the capability of one resource block in control region to transmit allocative information for data channel. Assume low-rank modulation QPSK is used. Furthermore, in order to observe system performance under the condition of insufficient control resource, in Fig. 5.3, Fig. 5.4, and Fig. 5.5, assume that only one CC can be used as control resource for all UEs in each eNB even though there are $J = 5$ CCs in this simulation.

Fig. 5.3 demonstrate total data rate of JCP scheme under different number of OFDM symbols in control region N_c, which is changed from 1 to 7. Observing Fig. 5.3, we can see that there exist the optimal number of OFDM symbols in control region under each code efficiency. For example, when code efficiency equals to 0.1523, the optimal number of OFDM symbols in control region is 4, which result in the maximum value of total data rate. When number of OFDM symbols equals to 1 to 3, the capability of one control CC can't carry the allocative information of all data channels. In other words, in these cases, not all data channels in all CCs can be used for data transmission. Thus, the total data rate will not reach the maximum value until number of OFDM symbols in control region equals to 4. After the optimal value, the system throughput will decrease. This is because control resource is so enough to carry whole allocative information of all data channels that the increase in number of OFDM symbols in control region will be useless and will decrease the transmission time of data region $2N_s - N_c$, which leads to the decrement in data rate. Besides, we can see that the optimal number of OFDM symbols in control region will be smaller when the code efficiency gets higher. This is because if the code efficiency gets higher, it requires less control resource to carry the allocative information of all data channels and will have more transmission time in data region.

The Fig. 5.4 shows total data rate of JCP, JCP-S, and HCP schemes under different code efficiency. Observing from this figure, the total data rate of three schemes increase in the first four efficiency on account of that the

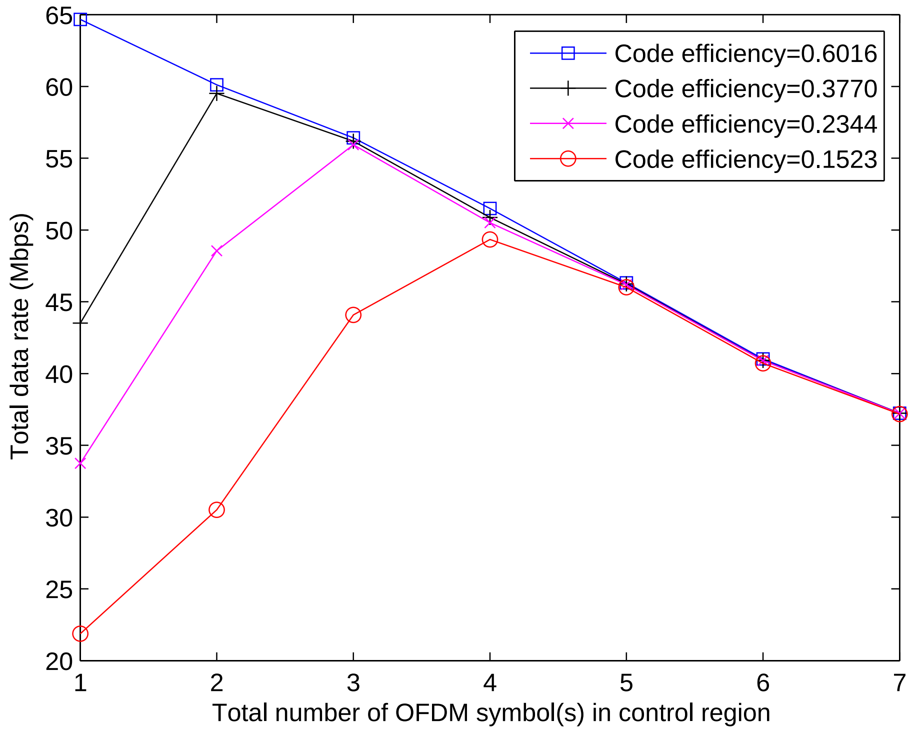

Figure 5.3: Total data rate of JCP scheme under different number of OFDM symbols in control region, which is changed from 1 to 7: total number of eNBs $M = 4$, total number of CCs $J = 5$, total number of UEs per eNB $K = 3$.

maximum amount of data channel, which can be used for data transmission at the same time, also increase when the value of code efficiency increases. However, we can see that there is not much increment in the total data rate when code efficiency raises from 0.6016 to 0.8770. This is because the maximum amount of data resource has reached the value of total data resource, i.e. $N_{total} = R \cdot J = 25$. As mentioned before, note that if code efficiency gets higher, it means that less amount of data channels can be used for data transmission. Comparing the detailed value of performance between JCP scheme and HCP scheme, we can observe that the difference in percentage between the performance of these two schemes raises when the code efficiency reduce. This atmosphere implies that JCP scheme can make much better selection for channel resource than HCP scheme especially in the situation of lower code efficiency.

In Fig. 5.5, it shows that the total data rate of JCP, JCP-S, and HCP schemes under different number of UEs per eNB. Observing this figure, we can see that when there is one UE in each eNB, the performance of HCP scheme is near to the performance of JCP scheme. It is because that in this special case, the channel allocation in both schemes are just the same, where the channel resource will be all allocated to this only UE no matter what the channel quality this UE has. Besides, we can see that the performance of JCP scheme gradually grows when there are more and more UEs in each eNB. This might because that the probability of having the kind of UEs, which has better channel quality, also grows when there are more and more UEs in each eNB. And in JCP scheme, the channel resource will prefer to be allocated to this kind of UE and result in better data rate. However, the HCP scheme has the opposite tendency because that the HCP scheme, whose target is to reduce total interference, will not indeed allocate channel resource to this kind of UE.

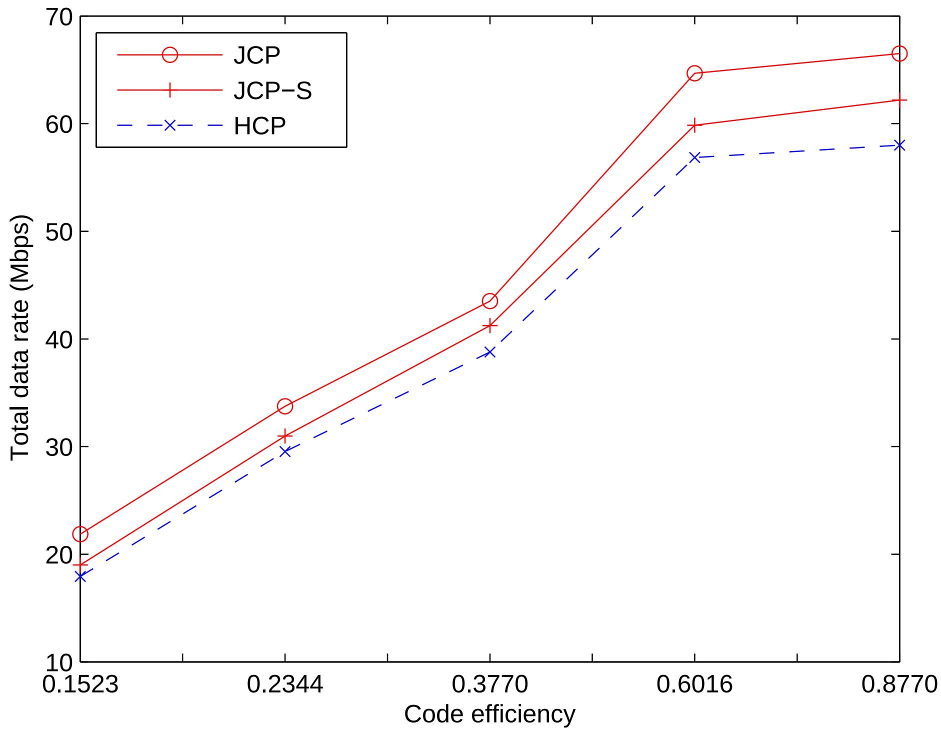

Figure 5.4: Total data rate of JCP, JCP-S, and HCP schemes under different code efficiency: total number of eNBs $M = 4$, total number of CCs $J = 5$, total number of UEs per eNB $K = 3$, number of OFDM symbol in control region $N_c = 1$.

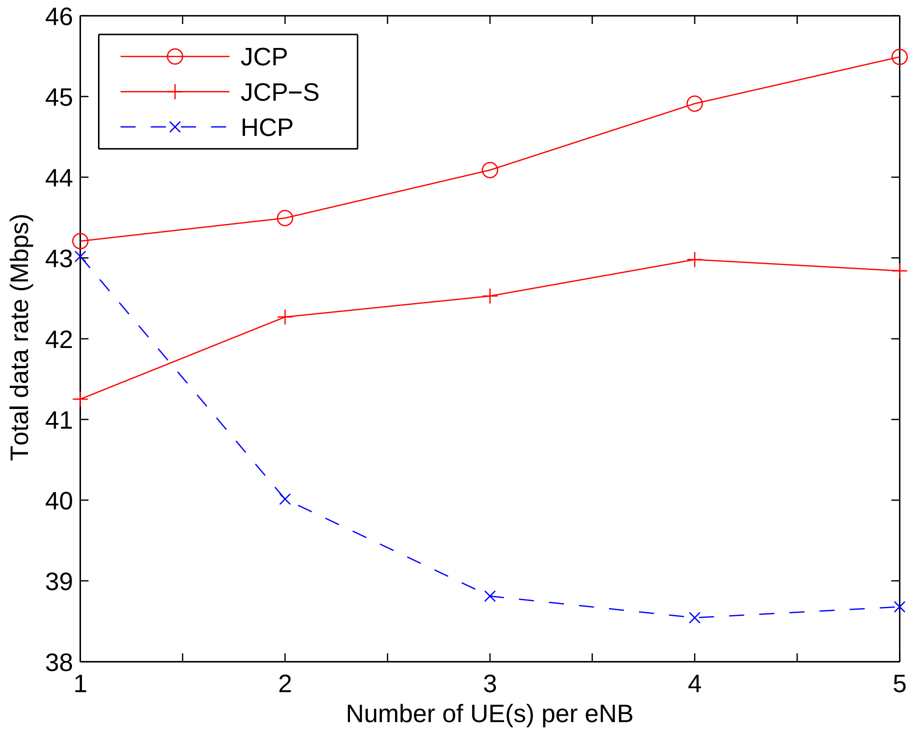

Figure 5.5: Total data rate of JCP, JCP-S, and HCP schemes under different number of UEs per eNB: total number of eNBs $M = 4$, total number of CCs $J = 5$, number of OFDM symbol in control region $N_c = 1$.

Chapter 6

Conclusion

In this thesis, the joint component carrier selection and power allocation (JCP) scheme based on geometric programming which transforms non-convex problem to convex problem is proposed to determined the allocation for both kinds of resource, channel and power respectively. And JCP scheme has great performance in the viewpoint of total data rate. However, JCP scheme has high complexity and computational cost since the consideration of the undeterministic interference term even though the problem is convex. Therefore, JCP-S scheme, a simplified version of JCP scheme, is then proposed where the interference term is assume to be fixed with expectation to lower the complexity in JCP scheme. Besides, on account of that the complexity is still high in the JCP-S scheme, the heuristic scheme tries to separated the whole problem into two parts. In other words, channel selection and power allocation problems are solved according to the corresponding algorithms successively. Two heuristic schemes, HCP and HCP-S schemes, are proposed where the power allocation problem is solved with interference term being undeterministic in HCP scheme or being fixed in HCP-S scheme. And the simulation result demonstrate that HCP scheme even has better performance than the JCP-S scheme under the scenario of low SINR even though HCP scheme is a heuristic scheme. There is a trade-off between JCP scheme and other simplified schemes considering the performance and the complexity.

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