國 立 交 通 大 學

電信工程研究所

碩 士 論 文

於上行傳輸多點協調系統中利用高效率干擾校齊之收發器設計

Efficient Interference Alignment Aided Transceiver Design in Uplink Coordinated Multipoint Systems

研 究 生：鍾綱撼　　Student: Gang-Han Chung

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中 華 民 國 一 百 零 二 年 七 月

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碩士論文

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摘要

由於鄰近細胞所造成的干擾會嚴重降低在現今無線細胞通訊系統中非常重要的系統效能，因此干擾必須被謹慎地處理。為了解決這個問題，第三代合作夥伴專案(third generation partnership project; 3GPP)在前瞻長程演進系統(Long Term Evolution-Advanced; LTE-A)中提出新穎的多點協調(coordinated multipoint; CoMP)傳輸與接收技術。在本篇論文中，吾人嘗試於上行傳輸多點協調系統中引入干擾校齊(interference alignment; IA)技術進而提升總傳輸速率。為了加快收斂速度，吾人進一步提出兩種高效率的干擾校齊演算法。其一為區塊 QR 分解輔助干擾校齊(block QR decomposition aided IA; BQRD aided IA)，它引入序列式干擾消除(successive interference cancellation; SIC)的概念。另一為兩階段式干擾校齊(two-stage IA)，它則是最佳化等效通道的結構並且引入功率載荷(power loading)。經由模擬驗證，吾人所提出的兩種演算法有較佳的收斂特性並且擁有和最大信號雜訊干擾比(signal-to-interference-plus-noise ratio; SINR)干擾校齊相近的總傳輸速率。由於僅需要較少迭代次數即可收斂，吾人提出的演算法更適合於實際應用。

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Abstract

The interference from other cells, which severely degrades the system performance, is a critical factor in modern wireless cellular communication systems and should be carefully managed. To tackle this problem, a new coordinated multipoint (CoMP) transmission and reception technique is proposed by the 3GPP in the LTE-A system. In this thesis, we attempt to incorporate interference alignment (IA) into uplink CoMP systems to improve the sum-rate performance. To boost convergence rate, we further propose two efficient IA aided transceiver designs for the uplink CoMP systems. One is the block QR decomposition (BQRD) aided IA that incorporates the concept of successive interference (SIC). The other is the two-stage IA that optimizes the structure of the effective channel and employs power loading. From simulation results, the proposed algorithms exhibit better convergence behavior and have comparable performance to the max-SINR IA. Requiring only a small number of iterations to converge, the proposed algorithms are suitable to practical applications.

Acknowledgement

I would like to thank for my advisor, Dr. Ta-Sung Lee, and my co-adivsor, Dr. Wei-Ho Chung, for their enthusiastic guidance, immense knowledge, and insightful comments. I learned a lot from their aggressive attitude in many aspects. I also wish to express appreciation to my senior, Chung-Jung Huang, for giving me countless precious guidance and suggestions on the research. I would also like to thank my friends and all members in the Communication System Design and Signal Processing (CSDSP) Lab for their encouragement and help. Last but not least, I would like to show my sincere thanks to my parents for supporting me spiritually throughout my life.

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Acronym Glossary

3GPP	third generation partnership project
AWGN	additive white Gaussian noise
BS	base station
BQRD	block QR decomposition
CoMP	coordinated multipoint
CU	central unit
CSI	channel state information
DoF	degree of freedom
DL	downlink
IA	interference alignment
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
MIMO	multiple-input multiple-output
MAC	multiple access channel
MMSE	minimum mean square error
MRC	maximum ratio combining
RP	reception point
RRH	remote radio head
SIC	successive interference cancellation
SNR	signal to noise ratio
SINR	signal to interference-plus-noise ratio
SVD	singular value decomposition
TP	transmission point
UE	user equipment
UL	uplink
ZF	zero forcing

Notations

M	number of cells in the considered system model
P	number of UEs in each cell
N_t	number of transmit antennas
N_r	number of receive antennas
$\mathbf{H}_{qk}^{m}$	channel between the qth receiver and the kth UE in cell m
$\mathbf{V}_{(m-1)P+k}$	precoder matrix for the kth UE in cell m
$\mathbf{x}_{(m-1)P+k}$	transmitted signal vector for the kth UE in cell m
$\mathbf{z}_q$	complex Gaussian noise vector at the qth receiver
N_0	variance of complex Gaussian noise
d_{T}	number of total transmit data streams
P_{UPW}	transmit power constraint for a single UE
$\mathbf{U}$	decoder matrix at the central unit
$\mathbf{F}$	linear equalizing matrix at the central unit
R_{sum}	achievable sum-rate
$\mathbf{X}^{(i)}$	the ith column of matrix $\mathbf{X}$
$\{\mathbf{X}\}_i^j$	matrix consists of the ith column to jth column of matrix $\mathbf{X}$
$\mathrm{diag}(\cdot)$	block diagonal matrix staking operator
$(\cdot)^T$	transpose operator
$(\cdot)^H$	Hermitian operator
$(\cdot)^{-1}$	inverse operator
$\mathrm{CN}\left(\mathbf{m},\mathbf{C}\right)$	complex Gaussian noise vector with mean $\mathbf{m}$ and covariance matrix $\mathbf{C}$
$\mathrm{E}\{\cdot\}$	expectation operator
$\mathrm{tr}(\cdot)$	trace operator
$\mathrm{S}(\mathbf{X}, p)$	scaling function that scales the Frobenius norm of $\mathbf{X}$ to p

Chapter 1

Introduction

Due to high user density in mobile communications, interference has become one of the obstacles in wireless communications. In addition, the demand for higher data rate and more reliable link quality make interference management a critical issue in next generation mobile communication networks. To provide more users with more reliable service, the next generation mobile communication standard, Long Term Evolution (LTE), is developed by the Third Generation Partnership Project (3GPP). To pursue the requirements for LTE-Advanced (LTE-A) [3-4], advanced techniques were developed, such as enhanced multiple-input multiple-output (MIMO) and coordinated multipoint (CoMP), etc.

CoMP is a technique that utilizes the cooperation between points in some cooperation group to coordinate the transmission/reception which is controlled by a central unit (CU) [5]. Due to the cooperation between points, it is expected that CoMP can have a better ability of inter-cell interference (ICI) alleviation and link quality enhancement. CoMP has been adopted in practical cellular systems as a tool to improve cell coverage and cell edge throughput. In terms of the capability of backhaul, CoMP can be classified into full cooperation CoMP and partial cooperation CoMP [6]. Exchanges of full information including full channel state information (CSI) and full data information are allowed in full cooperation CoMP with less backhaul constraints.

Centralized CoMP which can provide joint transmission or reception is one of the examples of the full cooperation CoMP [3-4]. On the other hand, partial cooperation exchanges partial data and CSI. For this type of CoMP, distributed CoMP and coordinated scheduling are two typical approaches [3-4].

For the ability to exploit spatial degrees of freedom (DoFs), MIMO provides transmission diversity, linear capacity growth, and throughput improvement in wireless communications. A large number of research works have been done on the applications of MIMO in cellular systems. Using MIMO in multi-user systems inevitably increases the interference level for each user, so there is a need to develop methods for mitigating inter-user interference [7]. Recently, a technique (i.e., interference alignment (IA)) is suggested to break the DoFs limitation in K-user MIMO interference channels, so each user can enjoy half the capacity of the interference free case [8-9]. The principle of IA is to suppress interference received at each receiver onto a lower dimensional subspace, so desired signals can be transmitted on interference free subspace to maximize the sum-rate of networks. However, it has no closed-form IA solutions in multi-user MIMO systems with more than three users so far. Therefore, iterative approaches based on reciprocity have been employed to alternately search the best IA solutions. In 2011, the work by S.A. Jafar et al. [9] proposed two iterative algorithms (i.e., minimum leakage, maximum SINR). The iterative procedure is expected to converge and generate a nearly optimal solution.

In this thesis, we attempt to incorporate IA into CoMP systems to explore the potential of improving overall system capacity in multi-user MIMO systems. Uplink centralized CoMP receptions are considered because CSI, a critical factor in employing IA, is available at the base station (BS) without the need of resource-consuming feedback, and the user equipments (UEs) need no modifications to support IA in uplink CoMP systems. After the investigation of the potential of the max-SINR IA to improve the system performance, it is found that numerous iterations are required to obtain the nearly optimal solution, which renders IA difficult to implement. Furthermore, certain research works are dedicated to implementation-level considerations and challenges in applying IA techniques to existing cellular networks recently [10]-[12]. As a remedy, two new IA aided transceiver designs are proposed. One is to use the block QR decomposition (BQRD) to eliminate the interdependency of precoders among UEs through the successive interference cancellation (SIC) technique. Due to interference pre-subtraction, it is expected that the proposed BQRD aided IA has a faster convergence rate. The other one, called the “two-stage IA”, is to directly optimize the structure of the effective channel and employ power loading. Different from previous numerical methods (e.g., the max-SINR IA algorithm proposed in Section 3.3.2), it is expected that the two-stage IA converges more quickly because the two-stage IA aims to get the characteristic of the effective channel in convergence.

The organization of this thesis is as follows. The classification of CoMP, mathematical system model of centralized uplink CoMP, and introduction of IA in the K-user interference channels are illustrated in Chapter 2. In Chapter 3, the definition of DoFs and incorporation of two popular IA algorithms (i.e., minimum leakage and maximum SINR in [9]) are shown. To boost the convergence rate, two IA algorithms, which employ the idea of the SIC and channel diagonalization are proposed in Chapter 4. In the same chapter, complexity analysis of the two proposed IA algorithms and max-SINR IA is provided to convince that the proposed algorithms are more suitable to practical applications. Finally, summary of this thesis and several potential future works are given in Chapter 5.

Chapter 2

System Model

The rapid growth of mobile data traffic and the demand for better link quality lead to the evolution of mobile wireless communication systems. For achieving higher spectrum efficiency, 3GPP adopted many advanced techniques such as enhanced MIMO and CoMP in LTE-A. By coordination between points (BSs or remote radio heads (RRHs)), CoMP improves cell coverage and cell edge throughput in LTE-A [3-4]. In this thesis, uplink CoMP assisted with multiple antennas is considered as system model.

Due to higher and higher user density, interference has become one of the obstacles in wireless communications. To tackle this problem, CoMP, which reduces the amount of interference in the coordination set by managing interference between cells, is considered. Over the past few decades, interference management has been discussed. Many researches are based on orthogonalization in time, frequency and code domain. For more aggressively mitigating interference, IA is adopted. IA is an advanced technique first proposed in the *K*-user systems. The basic idea of IA is to suppress interference received by each receiver onto a lower dimension subspace by coordination, so there are more DoFs to decode desired signal.

The organization of this chapter is as follows: Classification of CoMP transmission and reception is first shown in Section 2.1. In Section 2.2, centralized uplink CoMP system model is presented. Section 2.3 provides the basic concept of IA. Finally, Section 2.4 summaries this chapter.

2.1 Coordinated Multipoint (CoMP) Transmission and Reception in LTE-A

CoMP transmission and reception is considered for LTE-A as a tool to improve cell coverage, cell-edge throughput, and system efficiency. In CoMP operation, multiple points coordinate with each other by transmitting signal to other points through backhaul in some coordinated groups. By different kinds of coordination schemes, coordinating points do not incur severe interference or can even exploit interference as meaningful signals.

Both uplink and downlink CoMP scenarios can be categorized into four agreed development scenarios in 3GPP [5]:

Scenario 1: As illustrated in **Figure 2–1**, scenario 1 is the homogeneous network with intrasite CoMP which coordinates between sectors controlled by the same BS, where no backhaul is needed.

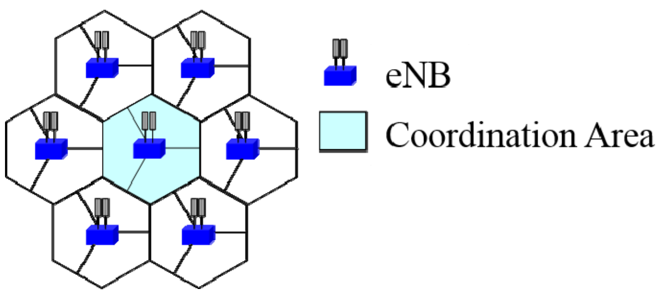

Figure 2–1: CoMP scenario 1 [5].

Scenario 2: As illustrated in **Figure 2–2**, scenario 2 is the homogeneous network with high transmit power RRHs, where coordination is between cells belonging to different radio sites.

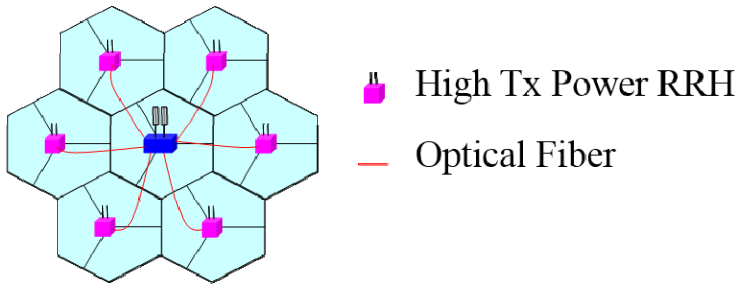

Figure 2–2: CoMP scenario 2 [5].

Scenario 3/4: As illustrated in **Figure 2–3**, scenario 3/4 is the network with low power RRHs within the macrocell coverage, where the transmission points (TPs) or reception points (RPs) created by the RRHs have different/same cell IDs as the macro cell.

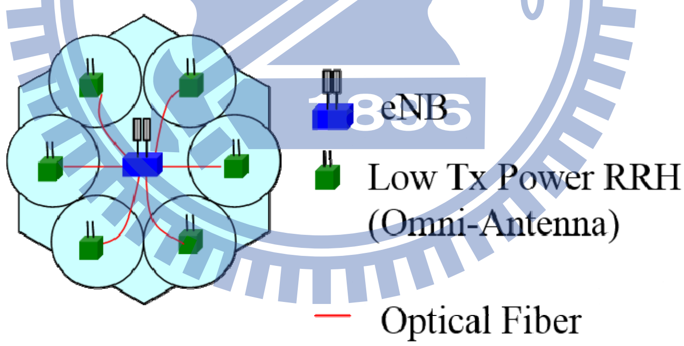

Figure 2–3: CoMP scenario 3/4 [5].

Centralized CoMP is a typical approach to do joint processing controlled by a CU which can be one of the TPs/RPs for downlink/uplink transmissions [6]. The CSI and/or the data information of various links are available in the CU via backhaul; however, it makes tremendous requirement for high speed backhaul with limited capacity. Contrary to the centralized processing, another approach which exchanges partial CSI and/or partial data information [6], called distributed CoMP, reduces the burden on backhaul by partial processing.

In general, downlink CoMP transmission schemes are classified as follows [3-4]:

1. Joint transmission: As depicted in **Figure 2–4**, each data stream is transmitted from multiple TPs at the same time to do coherent or non-coherent combining. This helps improving performance of cell-edge users by converting interference signals into meaningful signals.

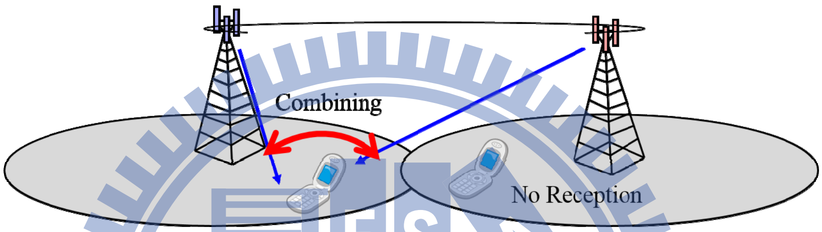

Figure 2–4: Joint transmission in downlink CoMP transmission.

2. Dynamic cell selection: As depicted in **Figure 2–5**, the signal for a given user is transmitted from a TP within the coordinated group, where the selection of the transmitted signal dynamically changes based on scheduling.

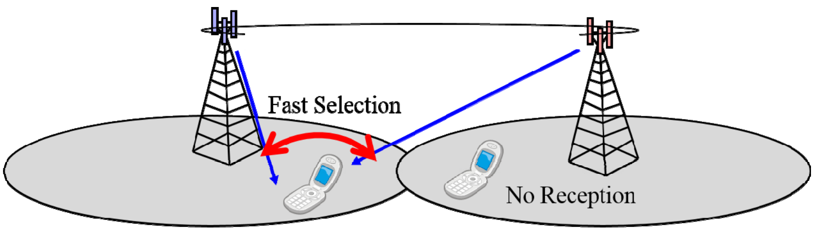

Figure 2–5: Dynamic cell selection in downlink CoMP transmission.

3. Coordinated scheduling/beamforming: As depicted in **Figure 2–6**, transmit beamforming for each user based on CSI feedback is generated to reduce the interference to other users scheduled within the coordinated group.

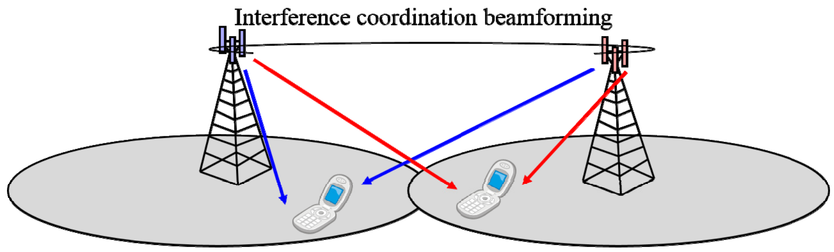

Figure 2–6: Coordinated scheduling/beamforming in downlink CoMP transmission.

On the other hand, uplink CoMP reception schemes are classified as follows [3-4]:

1. Interference rejection combining: As shown in **Figure 2–7**, the receive weights are generated under different criteria such as minimum mean square error (MMSE) or zero forcing (ZF) at the CU.

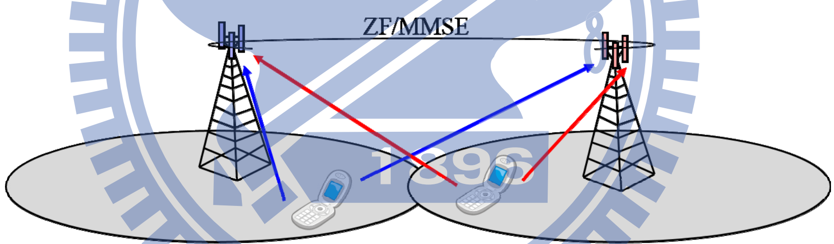

Figure 2–7: Interference rejection combining in uplink CoMP reception.

2. Coordinated scheduling: As shown in **Figure 2–8**, only one user transmits at a time based on coordinated scheduling among cells, and maximum ratio combining (MRC) is typically used.

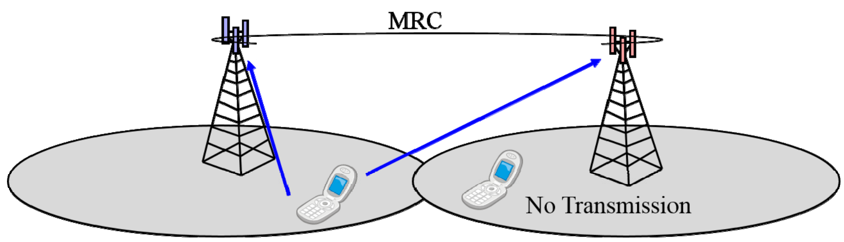

Figure 2–8: Coordinated scheduling in uplink CoMP reception.

In spite of the better performance of CoMP, there are still some challenges of practical CoMP implementations in existing/future wireless communications. Some resources need to be reserved for the legacy users that are compliant with the earlier specifications without supporting CoMP. Besides, the cooperation performance is sensitive to the estimation and quantization errors in information exchange because of constrained backhaul. Furthermore, the implementation cost grows with the coordinated group size due to increased synchronization difficulties and signaling overhead, higher processing complexity, and demand for backhaul mechanisms, and so on.

In this thesis, the CoMP scenario 3/4 is considered for the purpose of providing reliable service in high user density areas. To have better performance, the centralized cooperation with interference rejection combining is also included due to better interference mitigating ability and higher system efficiency.

2.2 Uplink CoMP System Model

In this section, the mathematical system model of centralized uplink CoMP involving multi-cell multi-user MIMO infrastructure is introduced; the basic structure of the associated transceiver design in this thesis is also presented in detail.

As shown in **Figure 2–9**, the uplink CoMP system involves M BSs (M cells) each equipped with N_r antennas, and each BS connects up to P UEs each equipped with N_t antennas. The transmitted signal vector of the qth UE in the lth cell is described by $\mathbf{x}_{(l-1)P+q} \in \mathbb{C}^{d_i \times 1} \left(\mathrm{E}\left\{ \mathbf{x}_{(l-1)P+q} \mathbf{x}_{(l-1)P+q}^H \right\} = \mathbf{I}_{d_{(l-1)P+q}} \right)$, which is processed by the precoding matrix $\mathbf{V}_{(l-1)P+q} \in \mathbb{C}^{N_t \times d_{(l-1)P+q}}$ before transmission; d_i is the number of transmitted layers belonging to ith UE. The channel matrix between the mth BS and the qth UE in the lth cell is denoted as $\mathbf{H}_{m,l}^{q} \in \mathbb{C}^{N_r \times N_t}$, whose elements are modeled as i.i.d. complex Gaussian random variables with distribution CN(0,1) for serving links ($m = l$), and CN(0,ε) for coordinating links ($m \neq l$) [13]. The received signal at the mth BS is expressed as

$$\mathbf{y}_m = \sum_{l=1}^{M} \mathbf{H}_{m,l} \mathbf{V}_l \mathbf{x}_l + \mathbf{z}_m, \tag{2.1}$$

where the aggregated precoding matrix at the lth cell is denoted as $\mathbf{V}_l = \mathrm{diag}\left(\mathbf{V}_{(l-1)P+1}, \ldots, \mathbf{V}_{(l-1)P+P}\right) \in \mathbb{C}^{N_t P \times d_l P}$; the aggregated transmitted signal at the lth cell is denoted as $\mathbf{x}_l = \left[(\mathbf{x}_{(l-1)P+1})^T, (\mathbf{x}_{(l-1)P+2})^T, \ldots, (\mathbf{x}_{(l-1)P+P})^T\right]^T \in \mathbb{C}^{Pd_l \times 1}$. The channel matrix between the mth BS and all UEs in the lth cell is denoted as $\mathbf{H}_{m,l} = \left[\mathbf{H}_{m,l}^{1}, \mathbf{H}_{m,l}^{2}, \cdots, \mathbf{H}_{m,l}^{P}\right] \in \mathbb{C}^{N_r \times N_t P}$, and the noise vector at the mth BS is denoted as $\mathbf{z}_m \in \mathbb{C}^{N_r \times 1}$ with distribution $\mathrm{CN}\left(\mathbf{0}_{N_r \times 1}, N_0 \mathbf{I}_{N_r}\right)$. Therefore, the total dimension of the transmission system is $d_{\mathrm{T}} = \sum_{l=1}^{MP} d_l$. The transmit power of each UE is restricted to P_{UPW}, i.e. $\left\|\mathbf{V}_{(l-1)P+q} \mathbf{x}_{(l-1)P+q}\right\|_F^2 = P_{\mathrm{UPW}}$.

In centralized CoMP, the cooperation is available among BSs and RRHs. The received signal from all the BSs and RRHs collected by the CU is denoted as

$$\mathbf{y}_{\mathrm{CoMP}} = \mathbf{H}\mathbf{V}\mathbf{x} + \mathbf{z}, \tag{2.2}$$

where $\mathbf{x} = [\mathbf{x}_1^T, \mathbf{x}_2^T, \ldots, \mathbf{x}_M^T]^T \in \mathbb{C}^{d_{\mathrm{T}} \times 1}$ is the aggregated transmitted signal vector, $\mathbf{V} = \mathrm{diag}\left(\mathbf{V}_1, \ldots, \mathbf{V}_M\right) \in \mathbb{C}^{N_t PM \times d_{\mathrm{T}}}$ is the aggregated precoding matrix, $\mathbf{H} = \left[\left[\mathbf{H}_{1,1}, \ldots, \mathbf{H}_{1,M}\right]^T, \ldots, \left[\mathbf{H}_{M,1}, \ldots, \mathbf{H}_{M,M}\right]^T\right]^T \in \mathbb{C}^{N_r M \times N_t PM}$ is the aggregated channel matrix, and $\mathbf{z} = [\mathbf{z}_1^T, \mathbf{z}_2^T, \ldots, \mathbf{z}_M^T]^T \in \mathbb{C}^{N_r M \times 1}$ is the aggregated noise vector. With full BS cooperation and interference rejection combining, uplink CoMP is transformed into a multiple access channel (MAC) like system [12]. For further utilizing available DoFs to mitigate interference efficiently, the received signal processed through a decoder

$\mathbf{U} \in \mathbb{C}^{N_r M \times d_\mathrm{T}}$ before equalizing yields

$$\mathbf{y}_{\mathrm{IA}} = \mathbf{U}^H \mathbf{y}_{\mathrm{CoMP}} = \mathbf{U}^H \mathbf{H}\mathbf{V}\mathbf{x} + \mathbf{U}^H \mathbf{z} = \mathbf{H}_{\mathrm{eff}} \mathbf{x} + \tilde{\mathbf{z}}. \tag{2.3}$$

With precoding and decoding, the equivalent channel matrix is denoted as:

$$\mathbf{H}_{\mathrm{eff}} = \mathbf{U}^H \mathbf{H}\mathbf{V}. \tag{2.4}$$

Finally, the CU processes the received signal as follows:

$$\hat{\mathbf{x}} = \mathbf{F}^H \mathbf{y}_{\mathrm{IA}} = \mathbf{F}^H \mathbf{H}_{\mathrm{eff}} \mathbf{x} + \mathbf{F}^H \tilde{\mathbf{z}}, \tag{2.5}$$

where $\hat{\mathbf{x}} \in \mathbb{C}^{d_\mathrm{T} \times 1}$ is the estimated signal by interference rejection combining, and $\mathbf{F} \in \mathbb{C}^{d_\mathrm{T} \times d_\mathrm{T}}$ is MMSE equalizing matrix as follows:

$$\mathbf{F}^H = \left(\mathbf{H}_{\mathrm{eff}}^H \mathbf{H}_{\mathrm{eff}} + N_0 \mathbf{I}_{d_\mathrm{T}} \right)^{-1} \mathbf{H}_{\mathrm{eff}}^H. \tag{2.6}$$

The achievable sum-rate of all layers in the UL CoMP systems [14] is considered as the performance index and defined as

$$R_{\mathrm{sum}} = \sum_{d=1}^{d_\mathrm{T}} \left[\log_2 \left(1 + \mathrm{SINR}_d \right) \right], \tag{2.7}$$

where SINR_d is the signal to interference-plus-noise ratio (SINR) measured at the output of equalizer corresponding to each layer, expressed as

$$\mathrm{SINR}_d = \frac{\left(\mathbf{F}^{(d)} \right)^H \mathbf{H}_{\mathrm{eff}}^{(d)} \left(\mathbf{H}_{\mathrm{eff}}^{(d)} \right)^H \mathbf{F}^{(d)}}{\left(\mathbf{F}^{(d)} \right)^H \left(\sum_{l \neq d} \mathbf{H}_{\mathrm{eff}}^{(l)} \left(\mathbf{H}_{\mathrm{eff}}^{(l)} \right)^H + N_0 \mathbf{I}_{N_r M} \right) \mathbf{F}^{(d)}} \tag{2.8}$$

In this thesis, we consider closed loop uplink CoMP communication system which provides better system performance while additional signaling and complexity are needed. That is, after evaluating precoder, decoder and equalizer set under predefined criterion, each precoding matrix is transmitted to corresponding UE. In addition, perfect channel estimation, perfect power control, and negligible timing advanced are assumed as well.

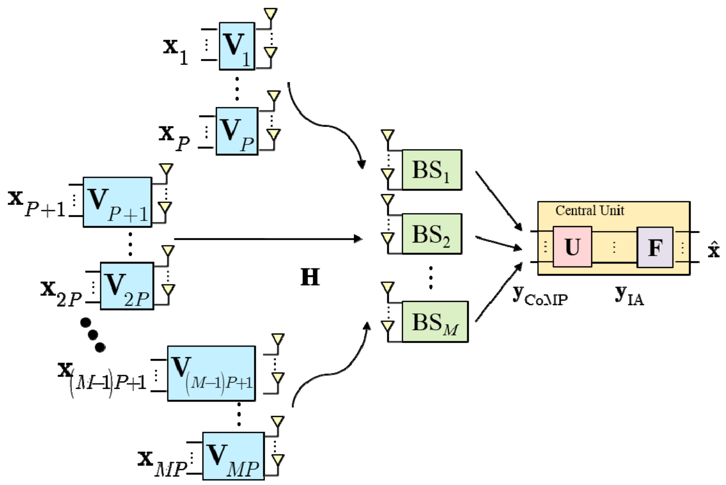

Figure 2–9: Illustration of centralized IA aided uplink CoMP system model.

2.3 Interference Alignment in *K*-User Systems

Interference alignment (IA) has recently emerged as a generalized multi-user MIMO technique for the X-channel and *K*-user interference channel scenarios [8-9]. The basic idea of IA is to align or compress interference onto some limited subspace, so the interference can be separated from the desired signal with sufficient DoFs. The DoFs can be provided by multiple antennas, frequency, time, or phase; the one provided by multiple-antenna is most commonly adopted. IA starts with an arbitrary precoder which induces an optimal decoder at receiver side and then this decoder triggers another algorithm to update the precoder at transmitter side. The algorithm goes back and forth between BSs and UEs to attain interference alignment. Thus IA is more suitable for time division duplex systems and the case with constant channels.

As depicted in **Figure 2–10**, in the *K*-user interference channel model, there are totally K BSs and K UEs, each BS serves a single UE, i.e. $P=1$. The transmitted signal $\mathbf{x}_k$ from UE in the *k*th cell is intended for the *k*th BS. Each BS processes its own received signal as follows:

$$\tilde{\mathbf{y}}_{k,K\text{-user}} = \mathbf{U}_k^H \sum_{l=1}^{K} \mathbf{H}_{k,l} \mathbf{V}_l \mathbf{x}_l + \mathbf{U}_k^H \mathbf{z}_k, \tag{2.9}$$

$$\hat{\mathbf{x}}_{k,K\text{-user}} = \mathbf{F}_k^H \mathbf{U}_k^H \sum_{l=1}^{K} \mathbf{H}_{k,l} \mathbf{V}_l \mathbf{x}_l + \mathbf{F}_k^H \mathbf{U}_k^H \mathbf{z}_k, \tag{2.10}$$

where $\mathbf{U}_k \in \mathbb{C}^{N_r \times d_k}$, $\mathbf{V}_k \in \mathbb{C}^{N_t \times d_k}$ and $\mathbf{F}_k \in \mathbb{C}^{d_k \times d_k}$ represent the decoding matrix, precoding matrix and equalizing matrix, respectively.

For the *K*-user interference channel, IA has been proved to be a capacity achieving approach which aligns the interference onto some limited subspace, so there would be some residual DoFs for the desired signal. The design criterion of optimal IA is given as follows [8-9] (taking *k*th BS for example):

$$\mathbf{U}_k^H \mathbf{H}_{k,l} \mathbf{V}_l = \mathbf{0}, \forall l \neq k, \tag{2.11}$$

$$\operatorname{rank}\left(\mathbf{U}_k^H \mathbf{H}_{k,k} \mathbf{V}_k\right) = d_k. \tag{2.12}$$

The interference is aligned onto the null space of the decoding matrix $\mathbf{U}_k$ (for $k = 1, 2, \ldots, K$) whose columns are the basis of the interference-free desired signal subspace at the *k*th BS. Therefore, the desired signal can be separated while the interference is completely eliminated by IA technique. Equation (2.11) is a set of bilinear equations of the interdependent unknown precoders and decoders. Furthermore, solutions for equation (2.12) exist if the MIMO channel is sufficiently random and the number of equations is larger or equal to the number of free variables of the equivalent channel matrix, $\mathbf{H}_{\text{eff}} = \mathbf{U}_k^H \mathbf{H}_{kk} \mathbf{V}_k$ for $k = 1, 2, \ldots, K$. A challenging issue of feasibility has been raised as to whether a system admits optimal IA or not [22].

Unfortunately, there appear to be no closed-form IA solutions in multi-user MIMO systems with more than three users. Therefore, iterative approaches based on duality between uplink and downlink transmissions have been employed to alternatively search the best IA solutions in multi-user systems. Several popular iterative IA algorithms are developed in the K-user interfering MIMO channels such as minimum leakage [9], maximum SINR [9], maximum sum-rate [17], and alternating minimization [19].

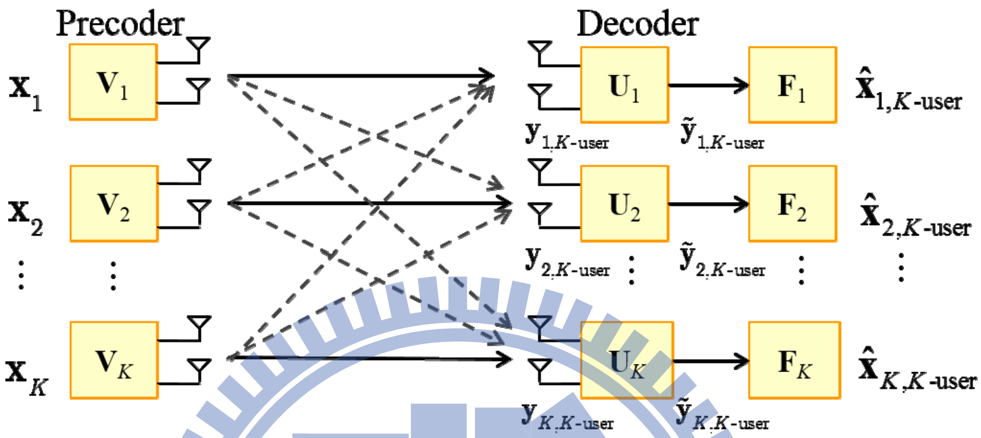

Figure 2–10: Illustration of IA in K-user interference channel.

2.4 Summary

In this chapter, the concept of CoMP is introduced, which includes the classification of uplink and downlink CoMP [3-4] and the scenarios defined in [5]. Then, the centralized uplink CoMP system adopted in this thesis is presented, and its system architecture and mathematical formulation are introduced. For dealing with such an interference-limited wireless network, a technique recently proposed in the K-user systems (i.e., interference alignment) is discussed. Due to the difficulty in searching the optimal IA solutions, some popular iterative approaches for IA have been developed by exploiting the duality between the uplink and downlink transmissions.

Chapter 3

Interference Alignment (IA) Aided Transceiver Design in Uplink CoMP Systems

The interference from other cells, which severely degrades the system performance, is a critical factor in modern wireless cellular communication systems and should be carefully managed. In such scenarios, the transceiver design based on centralized cooperation is a critical issue. To tackle this problem, a promising technique, CoMP transmission and reception, is developed.

In this section, the potential of the uplink CoMP systems and IA is first discussed. Due to the desire for providing more DoFs in centralized uplink CoMP systems, the suitability of incorporating IA into the considered centralized uplink CoMP systems is first presented. Then, the optimal IA is adopted into the considered systems; since the irregular feasibility of the optimal IA, two iterative IA algorithms (i.e., max-SINR and min-leakage) are alternatively adopted. Finally, the performance of this two iterative algorithms is evaluated.

The organization of this chapter is shown below. The motivation of the proposed IA aided UL CoMP transceiver scheme is given in Section 3.1. In Section 3.2, the detailed definition of DoFs is presented; then, the DoFs of some communication systems are also discussed. After the investigation in Section 3.2, the incorporation of IA in UL CoMP systems based on two popular iterative IA algorithms is introduced in Section 3.3; then, the performance of the two algorithms is evaluated. Finally, this chapter is summarized in Section 3.4.

3.1 Motivation

To achieve higher system capacity in an interference limited communication environment, many techniques are developed to cope with interference. Uplink CoMP is one of the techniques that aim to manage the interference caused by the UEs in other cells. However, the DoFs that can be provided by the centralized uplink CoMP systems are not fully obtained yet.

In the K-user MIMO interference channel, a recently proposed technique (i.e., IA) is suggesting to break the DoFs limitation, so each user can enjoy half the capacity of the interference free case [7]. From numerous researches, the ability of IA to break the DoFs limitation is also discussed under different interference channel models. Furthermore, certain research works are dedicated to implementation-level considerations and challenges in applying IA techniques to existing cellular networks recently [10]-[12]. Due to the similar capability of uplink CoMP and IA, IA is adopted to the considered centralized uplink CoMP systems for providing more DoFs in the centralized uplink CoMP systems.

3.2 Degrees of Freedom

In this section, the definition of DoFs is first introduced. Then, the DoFs of different interference channel models are presented to claim the potential of IA and the centralized uplink CoMP systems. From the definition in [7], the number of DoFs represents the rate of growth of network capacity with the log of the signal to noise ratio (SNR) theoretically. If $\mathrm{C}(\rho)$ is denoted as the sum capacity with SNR ρ, then the number of DoFs η is defined as

$$\eta = \lim_{\rho \to \infty} \frac{\mathrm{C}(\rho)}{\log_2(\rho)}, \tag{3.1}$$

which is also equivalent to

$$\mathrm{C}(\rho) = \eta \log_2(\rho) + \mathrm{o}(\log_2(\rho)), \tag{3.2}$$

where the $\mathrm{o}(\log_2(\rho))$ term becomes negligible in comparison with $\log_2(\rho)$ at high SNR. Therefore, the number of DoFs is also called the "pre-log factor". From the signal processing perspective, the DoFs can also represent interference free links per channel-use. In the following paragraphs, the DoFs of point-to-point MIMO channel, MAC channel, K-user interference channel, and K-user interference channel with full cooperation at the receiver side, are derived.

1. **Point-to-point MIMO channel**: The point-to-point MIMO channel shown in **Figure 3–1** is considered, where the receiver and the transmitter are equipped with M and N antennas, respectively. The maximum number of interference free links of the point-to-point MIMO channel can be the rank of the channel $(\text{i.e., } \min(M, N))$. In addition, the maximum number of the DoFs is achieved by the subchannel decomposition [7].

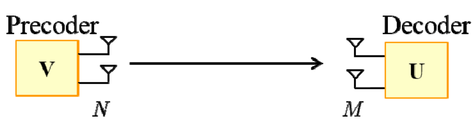

Figure 3–1: Illustration of point-to-point MIMO channel.

2. **MAC channel**: Consider the MAC channel, comprised of K transmitters and one receiver. As shown in **Figure 3–2**, the receiver and each transmitter are equipped with M and N antennas, respectively. From the transmitter perspective, the number of transmitted layers of each transmitter cannot be larger than the number of transmit antennas. On the other hand, from the receiver perspective, the number of received layers cannot be larger than the number of receive antennas. To satisfy the above two constraints, the maximum number of the DoFs is $\min(M, NK)$.

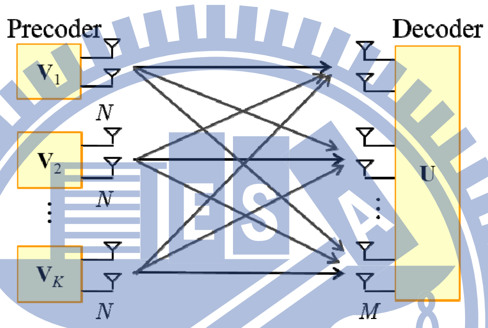

Figure 3–2: Illustration of MAC channel.

3. ***K*-user interference channel**: Consider the K-user interference channel, comprised of K transmitters and K receivers. As shown in **Figure 3–3**, each receiver and transmitter are equipped with M and N antennas, respectively. The number of interference free channels is only $\min(M, N)$ (the number of DoFs is $\min(M, N)$) by orthogonalization in the time, frequency, or code domain to avoid multi-user interference. However, if spatial DoFs are used to mitigate interference, the number of DoFs could be $\frac{K}{2}\min(M, N)$ asymptotically by IA [8].

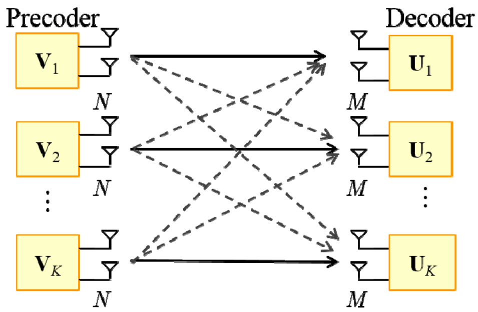

Figure 3–3: Illustration of K-user interference channel.

4. ***K*-user interference channel with full cooperation at the receiver side**: The K-user interference channel shown in **Figure 3–3** is considered. Due to the full cooperation at the receiver side, the channel model could be viewed as a MAC-like channel model, which is shown in **Figure 3–4**. From the result of the MAC channel, the number of DoFs is $\min(MK, NK)$.

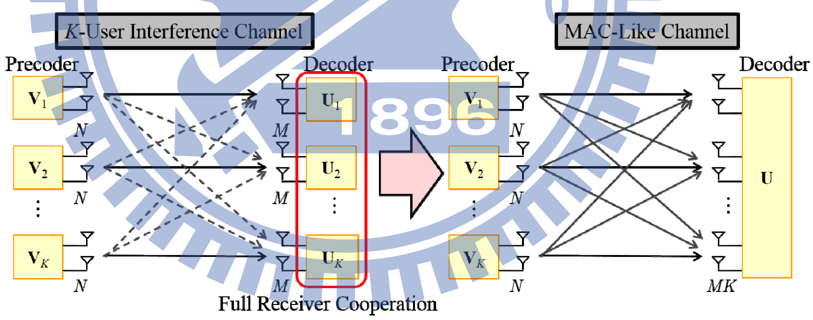

Figure 3–4: Illustration of equivalence between K-user channel with full cooperation at the receiver side and MAC-like channel.

From the above derivations, it can be seen that more DoFs could be provided by the incorporation of IA. Besides, because of the ability to utilize inter-cell interference, full cooperation at the receiver side (which is equivalent to the considered centralized uplink CoMP system) provides more DoFs. In the next section, we attempt to provide more DoFs based on the considered system to enhance the system performance.

3.3 Incorporation of Interference Alignment in Uplink CoMP Systems

For providing more DoFs to create more reliable links, IA is incorporated into the considered centralized uplink CoMP systems. IA can be adopted in either uplink CoMP systems or downlink CoMP systems to enhance the suppression of multi-user interference. As shown in **Figure 3–5** (single cell is depicted for concise presentation), to employ IA in the uplink CoMP systems, the system should operate as depicted in **Table 3-1**.

Table 3-1: An information exchange procedure of UL CoMP systems with IA techniques

Step 1:	The BSs forward estimated CSI to the CU, and the CU evaluates corresponding decoder and precoders.
Step 2:	The BSs feed the precoder back to each UE.
Step 3:	The UEs start to transmit signals.

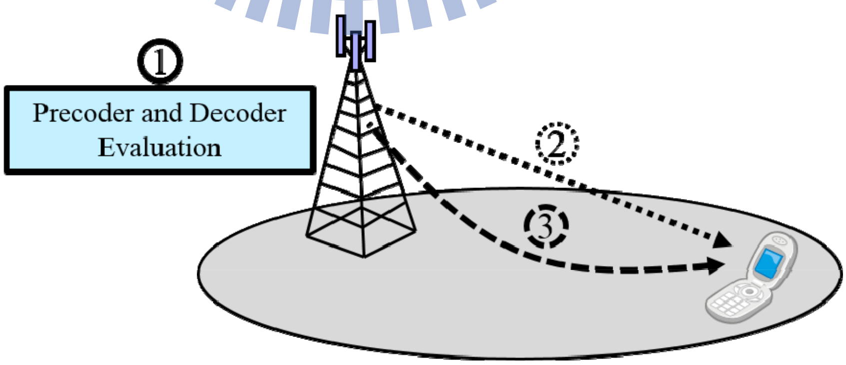

Figure 3–5: Illustration of information exchange procedure of UL CoMP systems with IA techniques.

Alternatively, as shown in **Figure 3–6** (single cell is depicted for concise presentation), to employ IA in the downlink CoMP systems, the system should operate as depicted in **Table 3-2**.

Table 3-2: An information exchange procedure of DL CoMP systems with IA techniques

Step 1:	The UEs feed estimated CSI back to the BSs
Step 2:	The BSs forward received CSI to the CU, and the CU evaluates corresponding decoders and precoder.
Step 3:	The BSs feed the decoder back to each UE.
Step 4:	The BSs start to transmit signals.

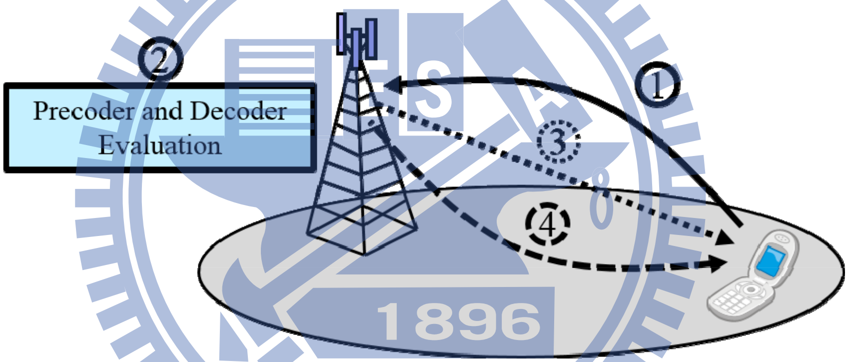

Figure 3–6: Illustration of information exchange procedure of DL CoMP systems with IA techniques.

Compared to the downlink CoMP systems, CSI feedback is not required in the uplink CoMP systems, and there is no modifications to the UEs. In this thesis, the uplink CoMP system is considered.

We here introduce the IA techniques into the interference channel model of cellular networks in the uplink CoMP scenario 3/4 involving intersite coordination between different RPs such as BSs/RRHs (i.e., the system model shown in Section 2.2), which is illustrated in **Figure 3–7**.

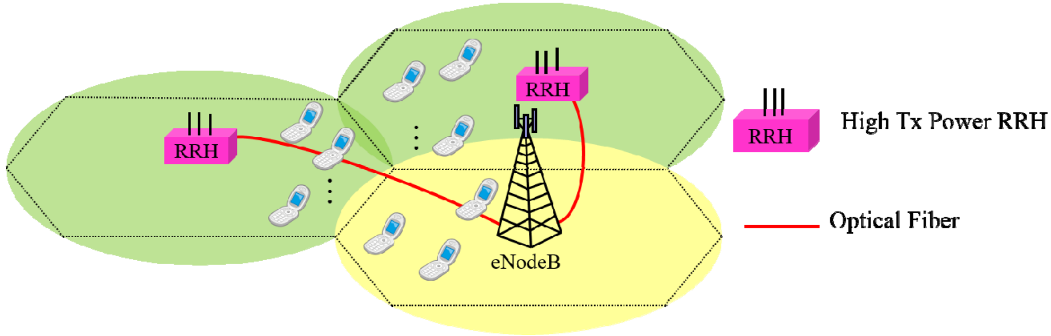

Figure 3–7: Centralized CoMP systems in heterogeneous networks.

Taking the advantages of the backhaul resource and centralized joint processing at the CU, more DoFs could be exploited for recovering the desired signals. Further, IA techniques can be incorporated to further improve the overall system throughput. According to the considered system model, the optimal design criterion of IA in the uplink CoMP systems can be described as follows [8-9]:

$$\left(\{\mathbf{U}\}_{\tilde{d}_{k,1}}^{\tilde{d}_{k,d_k}}\right)^H \mathbf{H}_l \mathbf{V}_l = \mathbf{0}_{d_k \times d_l}, \forall l \neq k, \tag{3.3}$$

$$\text{rank}\left(\left(\{\mathbf{U}\}_{\tilde{d}_{k,1}}^{\tilde{d}_{k,d_k}}\right)^H \mathbf{H}_k \mathbf{V}_k\right) = d_k, \forall k, \tag{3.4}$$

where $\mathbf{H}_l = [\mathbf{H}_{1,l}^T, \mathbf{H}_{2,l}^T, \ldots, \mathbf{H}_{K,l}^T]^T \in \mathbb{C}^{MN_r \times N_t}$, and the location index of decoding vector corresponding to the dth layer belonging to the kth UE within $\mathbf{U}$ is denoted as $\tilde{d}_{k,d} = \sum_{i=1}^{k-1} d_i + d$. The main difference between IA in the K-user interference channel and IA in the centralized CoMP system is that the latter incorporates full cooperation between BSs for computing the decoder at the CU. Because the optimal design criterion would not be feasible, two iterative algorithms proposed in [9], min-leakage and max-SINR, are adopted.

3.3.1 Min-Leakage IA in Uplink CoMP Systems

In this section, the minimum leakage IA algorithm in the K-user interference channel is modified and adopted into the considered system model. The minimum leakage algorithm in [9] can be reformulated as:

$$\left(\mathbf{U},\mathbf{V}_1,\ldots,\mathbf{V}_{MP}\right)=\arg\min_{\mathbf{U},\mathbf{V}_1,\ldots,\mathbf{V}_{MP}} I_k, \tag{3.5}$$

where I_k is the leakage of the kth UE at the output of the decoder, described as

$$I_k=\mathrm{tr}\left(\left(\{\mathbf{U}\}_{\tilde{d}_{k,1}}^{\tilde{d}_{k,d_k}}\right)^H \mathbf{Q}_k \{\mathbf{U}\}_{\tilde{d}_{k,1}}^{\tilde{d}_{k,d_k}}\right), \tag{3.6}$$

$$\mathbf{Q}_k=\sum_{l\neq k}\mathbf{H}_l\mathbf{V}_l\left(\mathbf{V}_l\right)^H\mathbf{H}_l^H. \tag{3.7}$$

Then, the optimal decoding matrix corresponding to kth UE $\{\mathbf{U}\}_{\tilde{d}_{k,1}}^{\tilde{d}_{k,d_k}}$ minimizing I_k can be formulated as

$$\{\mathbf{U}\}_{\tilde{d}_{k,1}}^{\tilde{d}_{k,d_k}}=\mathrm{eig}\left(\mathbf{Q}_k,d_k\right), \tag{3.8}$$

where $\mathrm{eig}\left(\mathbf{X},i\right)$ denotes the function of selecting eigenvectors corresponding to the 1st to ith smallest eigenvalues of $\mathbf{X}$. To evaluate the precoding matrix $\mathbf{V}_k$ for the kth UE, I_k is reformulated by channel reciprocity [10] as follows:

$$I_k=\mathrm{tr}\left(\left(\mathbf{V}_k\right)^H\tilde{\mathbf{B}}_k\mathbf{V}_k\right), \tag{3.9}$$

where

$$\tilde{\mathbf{B}}_k=\sum_{l\neq k}\mathbf{H}_k^H\mathbf{U}_l\mathbf{U}_l^H\mathbf{H}_k. \tag{3.10}$$

The optimal decoding matrix $\mathbf{V}_k$ minimizing I_k can be formulated as

$$\mathbf{V}_k=\kappa\,\mathrm{eig}\left(\tilde{\mathbf{Q}}_k,d_k\right), \tag{3.11}$$

where κ is chosen to satisfy $\mathrm{tr}\left(\mathbf{V}_k\mathbf{V}_k^H\right)=P_{\mathrm{UPW}}$.

The iterative procedure is summarized in **Table 3-3**. In this thesis, the algorithm provided in this section is denoted as the "min-leakage IA".

Table 3-3: A procedure for min-leakage IA in UL CoMP systems

Initialization: Set an initial value for decoding matrix **U**; we suggest adopting partial FFT matrix as the initial point for faster convergence.

Step 1: Compute the precoders $\mathbf{V}_i$, i=1,…,MP according to (3.11).

Step 2: Compute the decoder **U** according to (3.8).

Step 3: Go back to Step 1 till the constrained iteration number is achieved.

Step 4: Evaluate the equalizer and the achievable sum-rate according to (2.6) and (2.7).

3.3.2 Max-SINR IA in Uplink CoMP Systems

The maximum SINR IA algorithm in the K-user interference channel is modified and adopted into the considered system model in this section. The maximum SINR algorithm in [9] can be reformulated as:

$$\left(\mathbf{U},\mathbf{V}_1,\ldots,\mathbf{V}_{MP}\right)=\arg\max_{\mathbf{U},\mathbf{V}_1,\ldots,\mathbf{V}_{MP}} \gamma_{k,d}, \tag{3.12}$$

where $\gamma_{k,d}$ is the SINR of the dth layer belonging to the kth UE at the output of the decoder, described as

$$\gamma_{k,d}=\frac{\left(\mathbf{U}^{(\tilde{d}_{k,d})}\right)^H \mathbf{H}_k \mathbf{V}_k^{(d)} \left(\mathbf{V}_k^{(d)}\right)^H \mathbf{H}_k^H \mathbf{U}^{(\tilde{d}_{k,d})}}{\left(\mathbf{U}^{(\tilde{d}_{k,d})}\right)^H \mathbf{B}_{k,d} \mathbf{U}^{(\tilde{d}_{k,d})}}, \tag{3.13}$$

$$\mathbf{B}_{k,d}=\sum_{(l,m)\neq(k,d)} \mathbf{H}_l \mathbf{V}_l^{(m)} \left(\mathbf{V}_l^{(m)}\right)^H \mathbf{H}_l^H + N_0 \mathbf{I}_{N_r M}. \tag{3.14}$$

Then, the optimal decoding vector $\mathbf{U}^{(\tilde{d}_{k,d})}$ maximizing $\gamma_{k,d}$ can be formulated as

$$\mathbf{U}^{(\tilde{d}_{k,d})} = (\mathbf{B}_{k,d})^{-1}\mathbf{H}_k\mathbf{V}_k^{(d)} \Big/ \left\| (\mathbf{B}_{k,d})^{-1}\mathbf{H}_k\mathbf{V}_k^{(d)} \right\|_F . \tag{3.15}$$

To evaluate the precoding vector $\mathbf{V}_k^{(d)}$ for the dth layer at the kth UE, $\gamma_{k,d}$ is reformulated by channel reciprocity [10] as follows:

$$\gamma_{k,d} = \frac{\left(\mathbf{V}_k^{(d)}\right)^H \mathbf{H}_k^H \mathbf{U}^{\tilde{d}_{k,d}} \left(\mathbf{U}^{\tilde{d}_{k,d}}\right)^H \mathbf{H}_k \mathbf{V}_k^{(d)}}{\left(\mathbf{V}_k^{(d)}\right)^H \tilde{\mathbf{B}}_{k,d} \mathbf{V}_k^{(d)}}, \tag{3.16}$$

where

$$\tilde{\mathbf{B}}_{k,d} = \sum_{i=1, i\neq \tilde{d}_{k,d}}^{d_T} \mathbf{H}_k^H \mathbf{U}_i \mathbf{U}_i^H \mathbf{H}_k + N_0 \mathbf{I}_{N_t} . \tag{3.17}$$

The optimal decoding vector $\mathbf{V}_k^{(d)}$ maximizing $\gamma_{k,d}$ can be formulated as

$$\mathbf{V}_k^{(d)} = \left(\sqrt{P_{\text{UPW}} / d_k} \Big/ \left\| \left(\tilde{\mathbf{B}}_{k,d}\right)^{-1} \mathbf{H}_k^H \mathbf{U}^{(\tilde{d}_{k,d})} \right\|_F \right) \left(\tilde{\mathbf{B}}_{k,d}\right)^{-1} \mathbf{H}_k^H \mathbf{U}^{(\tilde{d}_{k,d})} . \tag{3.18}$$

The iterative procedure is summarized in **Table 3-1**. In this thesis, the algorithm provided in this section is denoted as the "max-SINR IA".

Table 3-4: A procedure for max-SINR IA in UL CoMP systems

Initialization: Set an initial value for decoding matrix **U**; we suggest adopting partial FFT matrix as the initial point for faster convergence.
Step 1: Compute the precoders $\mathbf{V}_i$, i=1,…,MP according to (3.18).
Step 2: Compute the decoder **U** according to (3.15).
Step 3: Go back to Step 1 till the constrained iteration number is achieved.
Step 4: Evaluate the equalizer and the achievable sum-rate according to (2.6) and (2.7).

3.4 Computer Simulations

The convergence behavior and sum-rate performance evaluations are presented for the comparison between the uplink CoMP transceiver scheme assisted with and without IA. In the following simulation results, “min-Leakage IA” and “max-SINR IA” represents the algorithms shown in Section 3.3.1 and Section 3.3.2. The achievable sum-rate is calculated based on (2.7) because a linear MMSE receiver is adopted in our work. In this thesis, “CoMP without IA” represents the approach that the precoder of each UE is formed by columns of identity matrix, and the received signal is directly equalized without the aid of the decoder. “Sum-Rate Ratio” is defined as the maximum eventual sum-rate with 4×10^4 iterations divided by the sum-rate with corresponding iterations to show the convergent behavior (if the sum-rate ratio is closer to 1, the algorithm performs better). The channel matrices are set by $\varepsilon = 0.4$ in all simulations in this thesis [13]. The simulation parameters chosen in this section are listed in **Table 3-5**.

Table 3-5: Simulation parameters

Parameter	**Value**
Channel	i.i.d. Rayleigh fading channel
Number of BSs (M)	3
Number of UEs Per Cell (P)	1
Number of transmit antennas (N_t)	4
Number of receive antennas (N_r)	2
Number of transmitted signal layers (d_i)	2
Number of channel realizations	100

Firstly, the convergence behavior is shown in **Figure 3–8**. As shown, the min-leakage

IA algorithm has superior convergence rate in comparison with the max-SINR IA algorithm; however, the min-leakage IA algorithm converges to bad performance. From the observation, the max-SINR IA algorithm has nearly no sum-rate enhancement with more than 4×10^4 iterations. Therefore, the convergence condition is defined to be with a slight 3% sum-rate degradation compared with the sum-rate with 4×10^4 iterations.

Secondly, the average achievable sum-rates of different algorithms in convergence are shown in **Figure 3–9**. The results are observed as follows. Because the min-leakage IA algorithm only tries to suppress interference, desired signals might be suppressed simultaneously. The min-leakage IA algorithm performs worse than the max-SINR IA algorithm and the CoMP without IA. With enough iterations (8000 iterations), the max-SINR IA algorithm has superior performance in the comparison with the CoMP without IA; however, with insufficient iterations, the max-SINR IA performs nearly the same as the CoMP without IA.

From the above simulation results, incorporating IA into uplink CoMP systems is shown to achieve the promising performance in mitigating severe interference. However, tremendous number of iterations are required for better performance. In the next section, two algorithms will be proposed to boost the convergence rate.

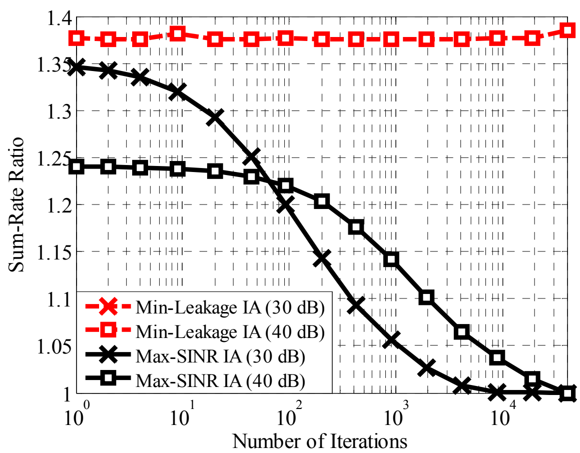

Figure 3–8: Convergence behavior of max-SINR IA and min-leakage IA in UL CoMP systems with $P_{\mathrm{UPW}} = 30$ and 40 dB.

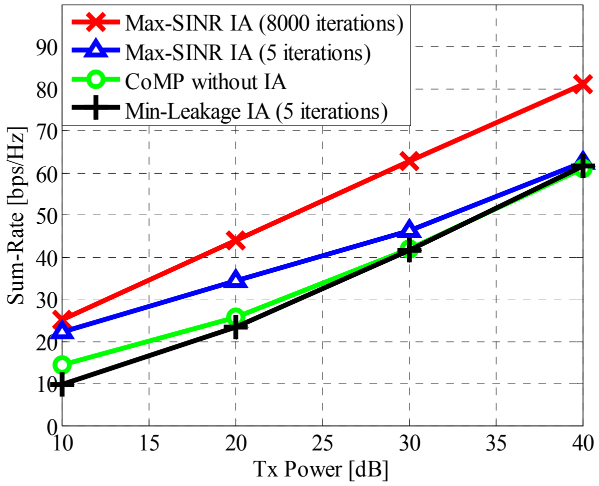

Figure 3–9: Sum-rate performance of CoMP without IA, max-SINR IA, and min-leakage IA in uplink CoMP systems with 5 and 8000 iterations.

3.5 Summary

Interference alignment aided uplink CoMP is discussed and evaluated in this chapter. First, two popular interference alignment algorithms (i.e., min-leakage IA and max-SINR IA) [8-9], developed in the K-user interference channel are incorporated in the uplink CoMP transceiver design. Their sum-rate performance is evaluated, and it is demonstrated that the max-SINR IA algorithm has better sum-rate performance because of a good compromise between interference and received power of the desired signal. Hence the max-SINR IA algorithm is regarded as a highly potential interference mitigation scheme. According to the observation, numerous iterations are required to guarantee that the max-SINR IA algorithm converges. In the next chapter, two IA algorithms are proposed to boost the convergence rate of IA for making IA easier to be implemented.

Chapter 4

Proposed Efficient Interference Alignment in Uplink CoMP Systems

In Chapter 3, the max-SINR IA algorithm is considered as a candidate for uplink CoMP. However, it is found that numerous iterations are required to achieve the improved sum-rate performance. As a remedy, two new IA aided transceiver designs are proposed. One is to use the BQRD to eliminate the interdependency of precoders among UEs through the SIC technique. Due to interference pre-subtraction, it is expected that the proposed BQRD aided IA has a faster convergence rate. The other one, called the "two-stage IA", is to directly optimize the structure of the effective channel defined in (2.4) and employ power loading. Different from previous numerical methods (e.g., the max-SINR IA algorithm proposed in Section 3.3.2), it is expected that the two-stage IA algorithm converges more quickly because the two-stage IA algorithm aims to get the characteristic of the effective channel in convergence. Due to the MAC-like nature of uplink CoMP, the iterative procedures of evaluating IA solutions are developed by exploiting the duality between multiple access and broadcast channels. [20-21].

The organization of this chapter is shown below. The motivation of the proposed IA aided UL CoMP transceiver schemes is given in Section 4.1. In Section 4.2, the proposed BQRD aided IA algorithm and its associated computer simulations are presented. To further minimize the performance gap at low SNR, a two-stage IA algorithm is proposed to directly optimize the effective channel in Section 4.3. Then, the computational complexity of the two proposed transceiver schemes is analyzed in Section 4.4. Numerical simulation results including the convergence behavior and sum-rate performance are given in Section 4.5 to compare the merits and drawbacks of the two proposed transceiver schemes. Finally, this chapter is summarized in Section 4.6.

4.1 Motivation

To achieve a higher system capacity in an interference limited communication environment, many techniques have been developed to cope with interference. Uplink CoMP is one of the techniques that aim to manage the interference caused by the UEs in other cells. To obtain the available DoFs that can be provided by the centralized uplink CoMP systems, a recently proposed technique (i.e., the max-SINR IA algorithm) is suggested to provide more DoFs in Section 3.3.2.

However, numerous iterations are required to guarantee that the max-SINR IA algorithm converges, which makes IA difficult to be implemented. From our observations, one of the reasons is the interdependency between UEs in multi-cell joint transmission scenarios. In Section 4.2, the proposed BQRD aided IA algorithm attempts to eliminate this interdependency to boost the convergence rate. Next, from the observation of [15], the SINR can be improved through proper power allocation if the effective channel has the nearly diagonal structure leading to less interference. Based on this idea, we further propose a two-stage IA algorithm to optimize the effective channel by mitigating different kinds of interference separately.

4.2 Proposed Block QR Decomposition Aided IA Algorithm

In this section, an efficient IA aided transceiver design algorithm for uplink CoMP systems is proposed to mitigate interference. The BQRD is used to resolve the interdependency of precoders among user UEs through the SIC technique. To further improve the efficiency, an additional constraint is employed by a projection operation. In the following paragraphs, the detailed algorithm is depicted in Section 4.2.1. Then, some computer simulation are shown to confirm the performance and convergence rate in Section 4.2.2.

4.2.1 Proposed Algorithm

In this section, a new IA algorithm is proposed to pursue maximum sum-rate with small number of algorithmic iterations. The optimization problem is formulated as follows:

$$\begin{aligned} &\max_{\mathbf{U},\mathbf{V}_1,\cdots,\mathbf{V}_{MP}} \quad R_{\text{sum}} \\ &\text{subject to} \ \left\|\mathbf{V}_l\right\|_F^2 = P_{\text{UPW}}, \quad l = 1,\ldots,MP, \\ &\left\|\mathbf{U}^{(i)}\right\|_F^2 = 1, \quad i = 1,\ldots,d_{\text{T}}. \end{aligned} \tag{4.1}$$

We consider the possibility to reduce iterations if the interdependency between UEs can be eliminated.

Firstly, performing the BQRD [1] to the channel matrix $\mathbf{H} \in \mathbb{C}^{MN_r \times MPN_t}$ produces

$$\mathbf{H} = \mathbf{Q}\mathbf{R}, \tag{4.2}$$

where $\mathbf{Q} \in \mathbb{C}^{N_r M \times N_r M}$ is an unitary matrix, and $\mathbf{R}$ is a $N_r M \times N_t PM$ block upper triangular matrix partitioned into sub-matrices $\mathbf{R}_{i,j} \in \mathbb{C}^{(N_r/P)\times N_t}$, so that $\mathbf{R}_{i,j} = \mathbf{0}_{(N_r/P)\times N_t}$ for $i > j$. Second, by incorporating (4.2) with (2.8), the corresponding approximated $\text{SINR}_{k,d}$ value for each data layer can be evaluated as follows [16]:

$$\text{SINR}_{k,d} \approx \left(\mathbf{R}_k \mathbf{V}_k^{(d)}\right)^H \mathbf{C}_{k,d}^{-1} \left(\mathbf{R}_k \mathbf{V}_k^{(d)}\right) = \text{metric}_{k,d}, \tag{4.3}$$

where $\mathbf{R}_k = \{\mathbf{R}\}_{(k-1)N_t+1}^{kN_t}$ and $\mathbf{C}_{k,d}$ is the interference-plus-noise covariance matrix of dth layer belonging to the kth UE as

$$\mathbf{C}_{k,d} = \sum_{(l,m)\neq(k,d)} \left(\mathbf{R}_l \mathbf{V}_l^{(m)}\right)\left(\mathbf{R}_l \mathbf{V}_l^{(m)}\right)^H + N_0 \mathbf{I}_{N_r M}. \tag{4.4}$$

Next, the optimization problem of maximizing the achievable sum-rate can be approximated by minimizing the summation of the reciprocal of individual $\ln\left(1+\text{metric}_{k,d}\right)$, expressed as

$$\begin{aligned} \max R_{\text{sum}} &\approx \max \sum_{k=1}^{MP} \sum_{d=1}^{d_k} \left[\log_2\left(1+\text{metric}_{k,d}\right)\right] \\ &= \max e^{\sum_{k=1}^{MP} \sum_{d=1}^{d_k} \left[\log_2\left(1+\text{metric}_{k,d}\right)\right]} = \min e^{-\sum_{k=1}^{MP} \sum_{d=1}^{d_k} \left[\ln\left(1+\text{metric}_{k,d}\right)\right]}. \end{aligned} \tag{4.5}$$

Then, when the $\text{metric}_{k,d}$ is larger than $(e-1)$ for data decoding, which is often satisfied in many practical scenarios, the problem in (4.1) can be approximated as

$$\max R_{\text{sum}} \approx \min e^{\sum_{k=1}^{MP} \sum_{d=1}^{d_k} \left(\frac{1}{\alpha \cdot \ln\left(1+\text{metric}_{k,d}\right)} - \beta\right)}, \tag{4.6}$$

where α and β are constants obtained by MMSE criterion within specific region but the values are invariant to the optimization problem. Next, the original optimization solution of (4.1) can be approximated as

$$\arg\max R_{\text{sum}} \approx \arg\min \sum_{k=1}^{MP}\sum_{d=1}^{d_k} \frac{1}{\ln\left(1+\text{metric}_{k,d}\right)}. \quad (4.7)$$

When the algorithm goes from $k = MP$ to $k = 1$, on the right-hand side of (4.7), the first group $(k = MP)$ is affected only by $\mathbf{V}_{MP}$, and the second group $(k = MP - 1)$ is affected only by $\mathbf{V}_{MP}$ and $\mathbf{V}_{MP-1}$, etc. The recursive dependency is the direct consequence of the block-wise upper triangular structure **R**. This is equivalent to the scenario where interference caused by the UE with lower index is pre-cancelled.

For further improving the sum-rate performance, we attempt to modify the decoding matrix $\hat{\mathbf{U}}$ obtained by pursuing the sum-rate according to (3.15). From the observation of [15], the sum-rate could be improved if the effective channel has the nearly diagonal structure which leads to less interference. By the following derivation, the effective channel with the aforementioned structure can be obtained in terms of **R**:

$$\mathbf{H}_{\text{eff}} = \mathbf{U}^H\mathbf{H}\mathbf{V} = \mathbf{U}^H\mathbf{Q}\mathbf{R}\mathbf{V} = \left(\mathbf{Q}^H\mathbf{U}\right)^H\mathbf{R}\mathbf{V} = \bar{\mathbf{U}}^H\mathbf{R}\mathbf{V}, \quad (4.8)$$

where $\mathbf{U}$ and $\bar{\mathbf{U}} = \mathbf{Q}^H\mathbf{U}$ are the final decoding matrix and the pre-projected decoding matrix, respectively. Here the column vectors of $\bar{\mathbf{U}}$ are set to be in the subspace S spanned by the left singular vectors of **R** corresponding to the 1st to d_Tth largest singular values of **R**. For reducing additional complexity, a matrix $\mathbf{M} \in \mathbb{C}^{N_r M \times N_r M}$ is designed to evaluate $\bar{\mathbf{U}}$ as:

$$\bar{\mathbf{U}} = \mathbf{M}\hat{\mathbf{U}}. \quad (4.9)$$

To satisfy such constraints, all column vectors of $\hat{\mathbf{U}}$ are further projected into the subspace S, and **M** can be expressed as:

$$\mathbf{M} = \mathbf{T}\mathbf{T}^H, \quad (4.10)$$

where $\mathbf{T} \in \mathbb{C}^{N_r M \times d_T}$ is formed by the left singular vectors of **R** corresponding to the

1st to d_Tth largest singular values of $\mathbf{R}$. Finally, the eventual decoding matrix is reconstructed as

$$\mathbf{U} = \mathbf{Q}\bar{\mathbf{U}}. \tag{4.11}$$

The iterative procedure is summarized in **Table 4-1**. In this thesis, the algorithm provided in this section is denoted as the "BQRD aided IA".

By introducing the BQRD technique, the criterion in (4.1) can be reformulated to a form similar to the SIC technique in signal detection. It is expected that the algorithm converges more quickly and has better performance in severely interfering scenarios due to interference pre-subtraction. We further force the decoding vectors to satisfy the convergence condition with just one more step to project them into the selected subspace. By appropriately constructing *S*, the convergence rate could be significantly improved with only slight performance degradation.

Table 4-1: A procedure for BQRD aided IA in UL CoMP systems

Initialization: Set the decoding matrix $\mathbf{U}$ to be part of FFT matrix.
Step 1: Perform the BQRD to obtain the unitary matrix $\mathbf{Q}$ and the block upper triangular matrix $\mathbf{R}$.
Step 2: Compute the precoders $\mathbf{V}_i$ from i=*MP* to 1 according to (3.18) by viewing $\mathbf{R}$ as the channel matrix.
Step 3: Compute the decoder $\bar{\mathbf{U}}$ according to (4.9) by viewing $\mathbf{R}$ as the channel matrix.
Step 4: Go back to step 2 till the constrained iteration time is achieved.
Step 5: Obtain the final decoder $\mathbf{U}$ according to (4.11).
Step 6: Evaluate the equalizer and the achievable sum-rate according to (2.6) and (2.7).

4.2.2 Computer Simulations

This section shows simulations for the convergence behavior and achievable sum-rate performance of the proposed algorithm and compares the results with different CoMP algorithms. In the following simulations, "max-SINR IA" and "BQRD aided IA" stand for the algorithms presented in Section 3.3.2 and Section 4.2.1, respectively. From observations, both the max-SINR IA and BQRD aided IA have nearly no improvements with iterations larger than 4×10^4. Therefore, the convergence condition is defined at the iterations of 3% degradation compared with the performance at 4×10^4 iterations for all simulation cases. The performance are evaluated in 3 scenarios (i.e. the scenario adopted in Section 3.4, typical CoMP scenario, and large CoMP size scenario). The simulation parameters chosen for typical CoMP scenario and large CoMP size scenario are listed in **Table 4-2** and **Table 4-3**, respectively.

Table 4-2: Simulation parameters for typical CoMP scenario

Parameter	**Value**
Channel	i.i.d. Rayleigh fading channel
Number of BSs (M)	3
Number of UEs Per Cell (P)	1
Number of transmit antennas (N_t)	4
Number of receive antennas (N_r)	4
Number of transmitted signal layers (d_i)	3
Number of channel realizations	100

Table 4-3: Simulation parameters for large CoMP size scenario

Parameter	Value
Channel	i.i.d. Rayleigh fading channel
Number of BSs (M)	3
Number of UEs Per Cell (P)	2
Number of transmit antennas (N_t)	4
Number of receive antennas (N_r)	8
Number of transmitted signal layers (d_i)	3
Number of channel realizations	100

Firstly, the convergence behavior, shown by the sum-rate ratio, in the scenario adopted in Section 3.4, typical CoMP scenario, and large CoMP size scenario is depicted in **Figure 4–1**, **Figure 4–3**, and **Figure 4–5**, respectively. As shown, the proposed BQRD aided IA has superior convergence rate compared with the max SINR-IA in the three scenarios with different transmit power.

Secondly, the average achievable sum-rate of different algorithms in the scenario adopted in Section 3.4, typical CoMP scenario, and large CoMP size scenario is shown in **Figure 4–2**, **Figure 4–4**, and **Figure 4–6**, respectively. The results are observed as follows. With a few iterations (5 iterations), the proposed BQRD aided IA has better performance in medium to high transmit power regime. To have better performance, the max-SINR IA needs much more iterations (8000 iterations) compared to the proposed algorithm (5 iterations). In convergence, the proposed algorithm only suffers 7.6% performance degradation because of the adopted approximation; even in interference dominated scenarios, the proposed algorithm can achieve slight performance enhancement due to interference pre-subtraction.

From the simulation results, the proposed algorithm is shown to achieve promising performance in mitigating severe interference in CoMP scenarios; within small number of iterations to converge, the proposed BQRD aided IA is applicable to practical applications. In the next section, we further propose an algorithm that takes channel diagonalization and power loading into consideration for minimizing the performance degradation at low SNR.

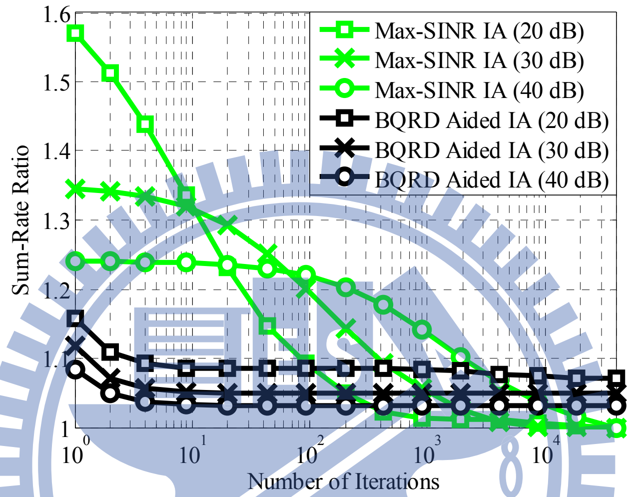

Figure 4–1: Convergence behavior of max-SINR IA and BQRD aided IA in UL CoMP systems with $P_{\text{UPW}} = 20$, 30 and 40 dB.

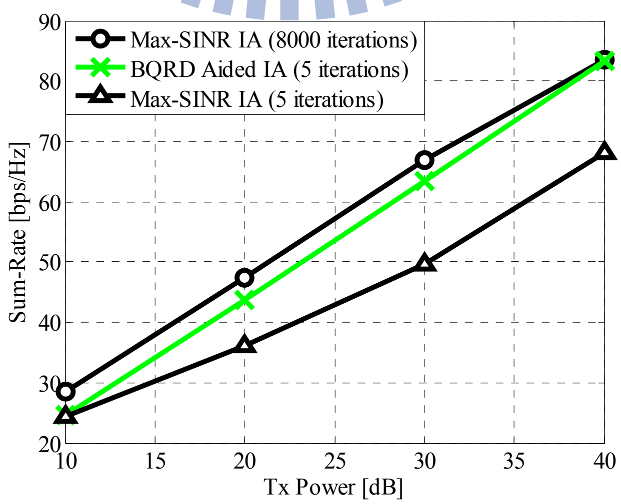

Figure 4–2: Sum-rate performance of BQRD aided IA with 5 iterations and max-SINR IA with 5 and 8000 iterations in UL CoMP.

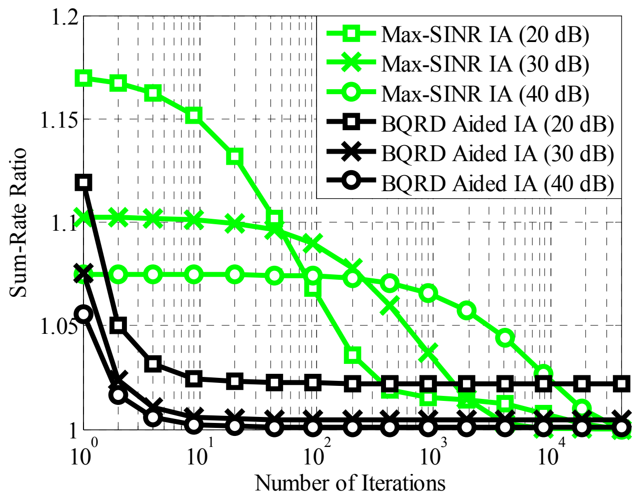

Figure 4–3: Convergence behavior of max-SINR IA and BQRD aided IA in UL CoMP systems with $P_{\text{UPW}} = 20$, 30 and 40 dB in typical CoMP scenario.

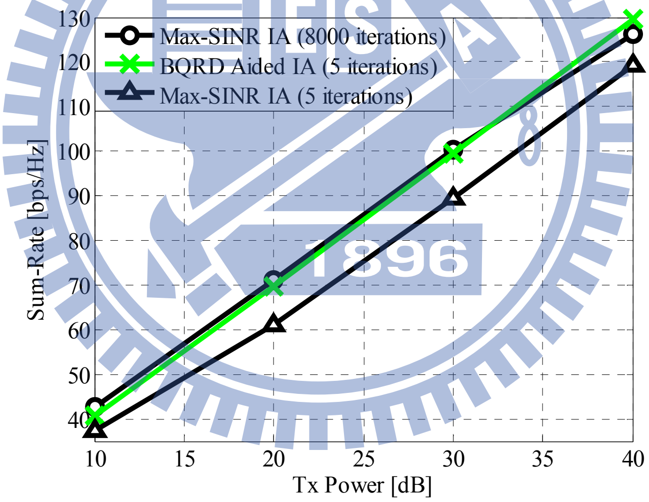

Figure 4–4: Sum-rate performance of BQRD aided IA with 5 iterations and max-SINR IA with 5 and 8000 iterations in typical CoMP scenario.

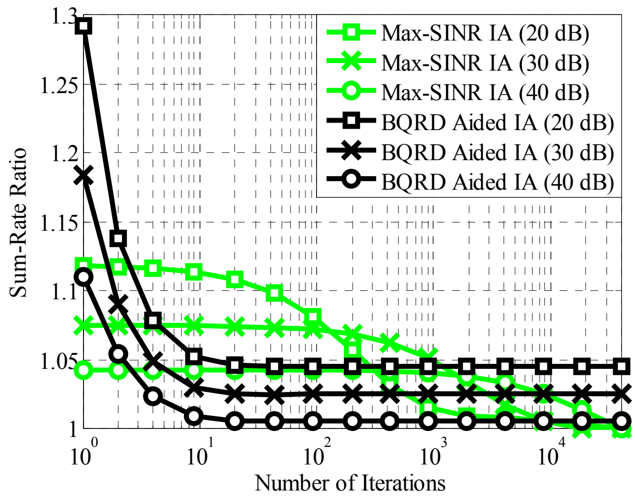

Figure 4–5: Convergence behavior of max-SINR IA and BQRD aided IA in UL CoMP systems with $P_{\text{UPW}} = 20$, 30 and 40 dB in large CoMP size scenario.

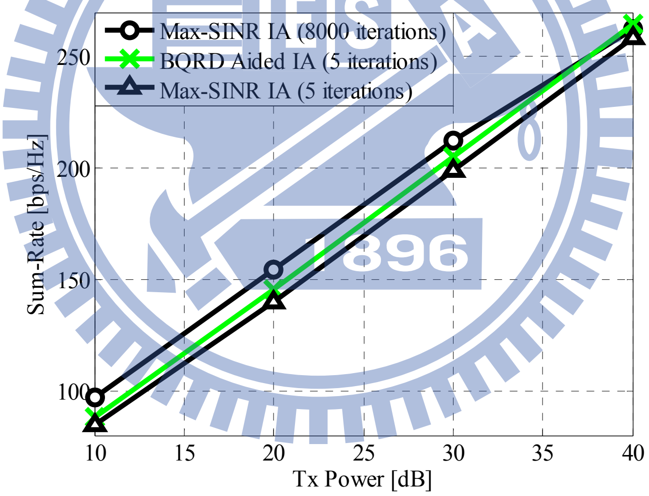

Figure 4–6: Sum-rate performance of BQRD aided IA with 5 iterations and max-SINR IA with 5 and 8000 iterations in large CoMP size scenario.

4.3 Proposed Two-Stage IA Algorithm

In this section, a new IA algorithm is proposed with the objective to maximize SINR within small number of algorithmic iterations by exploiting the structure of the effective channel. As observed in [15], the SINR can be improved through proper power allocation if the effective channel has the nearly diagonal structure leading to less interference. Through preserving available DoFs while suppressing interference, a two-stage approach is proposed to solve the max SINR problem as depicted in (3.12).

At the first stage, compared with the conventional approach, we softly utilize more DoFs to tackle partial interference through evaluating the weight of each vector. The design criterion is to minimize inter-user interference subject to preserving available DoFs. Specifically, to evaluate the first stage decoder $\mathbf{U}_{1,i} \in \mathbb{C}^{N_r M \times N_r M}$, the interference and noise power at the output of first stage decoder corresponding to ith UE $P_{int,i}$ is defined as

$$P_{int,i} = \operatorname{tr}\left(\mathbf{U}_{1,i}^H \mathbf{H}_{int,i} \mathbf{H}_{int,i}^H \mathbf{U}_{1,i}\right) + \operatorname{tr}\left(N_0 \mathbf{U}_{1,i}^H \mathbf{U}_{1,i}\right), \tag{4.12}$$

where $\mathbf{H}_{int,i}$ is the associated interference channel for the ith UE, expressed as $\mathbf{H}_{int,i} = \left[\mathbf{H}_1 \mathbf{V}_1, \ldots, \mathbf{H}_{i-1} \mathbf{V}_{i-1}, \mathbf{H}_{i+1} \mathbf{V}_{i+1}, \ldots, \mathbf{H}_{MP} \mathbf{V}_{MP}\right]$. Then, the optimization problem for the first stage decoder $\mathbf{U}_{1,i}$ can be formulated as:

$$\begin{aligned} &\min_{\mathbf{U}_{1,i}} P_{int,i}, \\ &\text{subject to } \left\|\mathbf{U}_{1,i}\right\|_F^2 = 1, \\ &\qquad \operatorname{rank}\left(\mathbf{U}_{1,i}\right) = N_r M. \end{aligned} \tag{13}$$

To tackle this problem, the first stage decoder can be decomposed into the product of basis and weighting matrices as $\mathbf{U}_{1,i} = \mathbf{B}_{1,i} \mathbf{W}_{1,i}$, where $\mathbf{B}_{1,i}$ is a basis matrix and $\mathbf{W}_{1,i}$

is a diagonal weighting matrix. Then, $P_{int,i}$ can be expressed as:

$$P_{int,i} = \mathrm{tr}\left(\mathbf{W}_{1,i}^H\mathbf{B}_{1,i}^H\left(\mathbf{T}_{int,i}\boldsymbol{\Sigma}_{int,i}\boldsymbol{\Sigma}_{int,i}^H\mathbf{T}_{int,i}^H + N_0\mathbf{I}_{N_rM}\right)\mathbf{B}_{1,i}\mathbf{W}_{1,i}\right), \tag{4.14}$$

where $\mathbf{H}_{int,i} = \mathbf{T}_{int,i}\boldsymbol{\Sigma}_{int,i}\mathbf{Q}_{int,i}^H$ is the singular value decomposition (SVD) of $\mathbf{H}_{int,i}$. When $\mathbf{B}_{1,i}$ is set to match singular vectors of the interference channel $\mathbf{H}_{int,i}$ as

$$\mathbf{B}_{1,i} = \mathbf{T}_{int,i}, \tag{4.15}$$

the $P_{int,i}$ can be further expressed as

$$P_{int,i} = \mathrm{tr}\left(\mathbf{W}_{1,i}^H\boldsymbol{\Sigma}_{int,i}\boldsymbol{\Sigma}_{int,i}^H\mathbf{W}_{1,i} + N_0\mathbf{W}_{1,i}^H\mathbf{W}_{1,i}\right). \tag{4.16}$$

For minimizing $P_{int,i}$ and preserving available DoFs, $\mathbf{W}_{1,i}$ is set, based on water filling principle allocating more power to the channel with less interference and noise power, as

$$\mathbf{W}_{1,i} = \mathrm{S}\left(\left(\boldsymbol{\Sigma}_{int,i}\boldsymbol{\Sigma}_{int,i}^H + N_0\mathbf{I}_{N_rM}\right)^{-1/2}, 1\right). \tag{4.17}$$

where $\mathrm{S}(\mathbf{X}, p) = \left(\sqrt{p}\big/\|\mathbf{X}\|_F\right)\mathbf{X}$ is denoted as a scaling function which scales the Frobenius norm of $\mathbf{X}$ to p. Then we adopt the same approach to obtain the first stage precoder $\mathbf{V}_{1,i} \in \mathbb{C}^{N_t \times N_t}$ by reciprocity property. The interference and noise power at the output of first stage virtual decoder (as the first stage precoder in forward link) belonging to the ith UE, denoted as $\bar{P}_{int,i}$, is defined as

$$\bar{P}_{int,i} = \mathrm{tr}\left(\mathbf{V}_{1,i}^H\bar{\mathbf{H}}_{int,i}\bar{\mathbf{H}}_{int,i}^H\mathbf{V}_{1,i}\right) + \mathrm{tr}\left(N_0\mathbf{V}_{1,i}^H\mathbf{V}_{1,i}\right), \tag{4.18}$$

where $\bar{\mathbf{H}}_{int,i}$ is the associated interference channel for the ith UE, expressed as $\bar{\mathbf{H}}_{int,i} = \left[\mathbf{H}_i^H\mathbf{U}_{1,1}, \ldots, \mathbf{H}_i^H\mathbf{U}_{1,i-1}, \mathbf{H}_i^H\mathbf{U}_{1,i+1}, \ldots, \mathbf{H}_i^H\mathbf{U}_{1,MP}\right]$. Then, the optimization problem for the first stage precoder $\mathbf{V}_{1,i}$ corresponding to the ith UE can be formulated as

$$\begin{aligned} &\min_{\mathbf{V}_{1,i}} \bar{P}_{int,i}, \\ &\text{subject to } \left\|\mathbf{V}_{1,i}\right\|_F^2 = P_{\text{UPW}} / d_i, \\ &\text{rank}\left(\mathbf{V}_{1,i}\right) = N_t. \end{aligned} \tag{4.19}$$

Afterwards, the first stage precoder is expressed as $\mathbf{V}_{1,i} = \bar{\mathbf{B}}_{1,i}\bar{\mathbf{W}}_{1,i}$, where $\bar{\mathbf{B}}_{1,i}$ and $\bar{\mathbf{W}}_{1,i}$ are as follows:

$$\bar{\mathbf{B}}_{1,i} = \bar{\mathbf{T}}_{int,i}, \tag{4.20}$$

$$\bar{\mathbf{W}}_{1,i} = \text{S}\left(\left(\bar{\mathbf{\Sigma}}_{int,i}\bar{\mathbf{\Sigma}}_{int,i}^H + N_0\mathbf{I}_{N_t}\right)^{-1/2}, P_{\text{UPW}}\right), \tag{4.21}$$

where $\bar{\mathbf{H}}_{int,i} = \bar{\mathbf{T}}_{int,i}\bar{\mathbf{\Sigma}}_{int,i}\bar{\mathbf{Q}}_{int,i}^H$ is the SVD of $\bar{\mathbf{H}}_{int,i}$.

At the second stage, the design criterion is to decouple desired signals to eliminate intra-user interference. The second stage decoder $\mathbf{U}_{2,i}$ and precoder $\mathbf{V}_{2,i}$ corresponding to the ith UE are defined as:

$$\mathbf{U}_{2,i} = \left\{\tilde{\mathbf{T}}_i\right\}_1^{d_i}, \tag{4.22}$$

$$\mathbf{V}_{2,i} = \left\{\tilde{\mathbf{Q}}_i\right\}_1^{d_i}, \tag{4.23}$$

where $\tilde{\mathbf{H}}_i = \mathbf{U}_{1,i}^H\mathbf{H}_i\mathbf{V}_{1,i}$ is the effective channel after the first stage process, and $\tilde{\mathbf{H}}_i = \tilde{\mathbf{T}}_i\tilde{\mathbf{\Sigma}}_i\tilde{\mathbf{Q}}_i^H$ is the SVD of $\tilde{\mathbf{H}}_i$ with singular values in a descending order from the top. By the linearity of the two stages, the eventual decoder can be obtained as

$$\mathbf{U} = \text{S}\left(\mathbf{U}_1\mathbf{U}_2, d_{\text{T}}\right), \tag{4.24}$$

where $\mathbf{U}_1 = \left[\mathbf{U}_{1,1}, \mathbf{U}_{1,2}, \ldots, \mathbf{U}_{1,MP}\right]$ and $\mathbf{U}_2 = \text{blkdiag}\left(\mathbf{U}_{2,1}, \mathbf{U}_{2,2}, \ldots, \mathbf{U}_{2,MP}\right)$ are the first-stage and the second-stage aggregated decoders, respectively. Equivalently, the eventual precoder for the ith UE can be expressed as

$$\mathbf{V}_i = \mathrm{S}\left(\mathbf{V}_{1,i}\mathbf{V}_{2,i}, P_{\mathrm{UPW}}\right). \tag{4.25}$$

From the above derivation, the decoders and precoders of the first and second stages are evaluated. Then, the eventual decoders and precoders can be obtained. Detailed iterative procedure is summarized in **Table 4-4**.

The proposed two-stage IA algorithm directly optimizes the structure of the effective channel with additional power allocation scheme in each iteration rather than the max-SINR IA algorithm mentioned in Section 3.3.2. Compared to the max-SINR IA algorithm, the proposed two-stage IA algorithm is expected to converge more quickly and have better performance.

Table 4-4: A procedure for two-stage IA in UL CoMP systems

Initialization: Set an initial value for precoding matrices $\mathbf{V}_i$; we suggest adopting partial FFT matrix as the initial point for faster convergence.
Step 1: Compute the first stage decoder $\mathbf{U}_{1,i}$ according to (4.15) and (4.17).
Step 2: Compute the first stage precoder $\mathbf{V}_{1,i}$ according to (4.20) and (4.21).
Step 3: Compute the second decoder $\mathbf{U}_{2,i}$ and stage precoder $\mathbf{V}_{2,i}$ according to (4.22) and (4.23).
Step 4: Obtain the eventual decoder $\mathbf{U}$ and precoders $\mathbf{V}_i$ according to (4.24) and (4.25).
Step 5: Go back to step 1 till the constrained iteration number is achieved.
Step 6: Evaluate the equalizer and the achievable sum-rate according to (2.6) and (2.7).

4.4 Complexity Analysis of Proposed Interference Alignment Algorithms

Computational complexity is a critical issue from the practical viewpoint, and it highly depends on the system parameters and the algorithms adopted. In this section, we discuss the computational complexity per iteration or per operation for the mentioned three IA algorithms (i.e., the max-SINR IA in Section 3.3.2, the BQRD in Section 4.2, and the two-stage IA in Section 4.3). The computational complexity is measured in terms of the number of floating point operations (flops). All additions, subtractions, multiplications, and divisions are equally treated as flops.

According to [24], the computational complexity of the max-SINR IA, BQRD processing, and two-stage IA per iteration or per operation is listed in **Table 4-5**. As shown, the proposed BQRD processing has nearly the same computational complexity as the max-SINR IA; and the proposed two-stage IA has higher computational complexity due to the adopted singular value decomposition.

Table 4-5: Complexity of max-SINR IA, BQRD, and two-stage IA per operations

Operation	Computational complexity
Max-SINR IA	$d_{\mathrm{T}}\begin{pmatrix} M^2N_r\left(2MN_r+3PN_t+4N_r\right)+N_t^2\left(2MP+N_t+2\right)+5MN_r \\ +N_t+d_{\mathrm{T}}+1 \end{pmatrix}$
BQRD	$N_r^2M^3\left(3\left(MP-1\right)\left(2N_r+P\right)+140N_r\right)/6+N_t^2N_r\left(4M+2/P\right)+$ $MN_r^2N_t\left(MP-1\right)\left(MP-2\right)/P+2MN_r^2N_t\left(MP+1\right)$
Two-stage IA	$M^2N_r^2+3MN_r+22\sum_{i=1}^{MP}\left(d_{\mathrm{T}}-d_i\right)^3+d_{\mathrm{T}}\left(N_t^2+2MN_rN_t-3M^2N_r^2\right)+$ $4N_t^2\left(MP-1\right)MN_r+22M^3N_r^3\left(MP-1\right)^3+N_t^2+3N_t+$ $MP\left(4M^2N_r\left(N_t+d_{\mathrm{T}}\right)+22N_t^3\right)$

4.5 Computer Simulations

This section shows simulations for the convergence behavior and achievable sum-rate performance of the proposed algorithms and compares the results with different CoMP algorithms. In the following simulation, “max-SINR IA” , “BQRD aided IA” , and “two-stage IA” stand for the algorithm presented in Section 3.3.2, Section 4.2.1, and Section 4.3, respectively; “CoMP without IA” represents the approach that the precoder of each UE is formed by columns of identity matrix, and the received signal is directly equalized without the aid of the decoder. From observations, the max SINR IA, BQRD aided IA, and two-stage IA have nearly no improvements with iterations larger than 4×10^4. Therefore, the convergence condition is defined at the iterations of 3% degradation compared with the performance at 4×10^4 iterations for all simulation cases. The performance are evaluated in 3 scenarios (i.e. the scenario adopted in Section 3.4, the typical CoMP scenario, and the large CoMP size scenario). The simulation parameters chosen for the typical CoMP scenario and large CoMP size scenario are listed in **Table 4-2** and **Table 4-3**, respectively.

Firstly, the convergence behavior, shown by the sum-rate ratio, in the scenario adopted in Section 3.4, typical CoMP scenario, and large CoMP size scenario is depicted in **Figure 4–7**, **Figure 4–9**, and **Figure 4–11**, respectively. As shown, the proposed two-stage IA has superior convergence rate compared with the max SINR IA in the three scenarios with different transmit power and converges even faster than the BQRD aided IA.

Secondly, the average achievable sum-rate of different algorithms in the scenario adopted in Section 3.4, typical CoMP scenario, and large CoMP size scenario is shown in **Figure 4–8**, **Figure 4–10**, and **Figure 4–12**, respectively. The results are observed as follows. With a few iterations (5 iterations), the proposed two-stage IA has better performance. To have better performance, the max-SINR IA needs much more iterations (8000 iterations) compared to the proposed two-stage IA (5 iterations). In the convergence regime, the proposed two-stage IA has nearly the same performance as the max-SINR IA; even in interference dominated scenarios, the proposed two-stage IA can achieve slight performance enhancement due to additional power loading in each iteration.

Considering the computational complexity in convergence, the complexity reduction ratio, defined as the rate of the complexity of the proposed algorithm with the complexity of the max-SINR IA, in convergence is listed in **Table 4-6**. As shown, both of the proposed algorithms reduce at least 98% complexity in the considered scenarios. The above data confirm that both of the proposed algorithms are suitable to be adopted to existing cellular networks; the reasons are as follows. First, despite an additional BQRD preprocessing of the BQRD aided IA and higher complexity of the two-stage IA, both of the proposed algorithms have superior convergence rate. Thanks to VLSI technologies, the impact of computational complexity could be minimized. Second, both of the proposed algorithms have better convergent rate, which means that more CoMP sets can be offered in each scheduling period.

From the simulation results, the proposed algorithms are shown to achieve promising performance in mitigating severe interference in CoMP scenarios. Requiring only a small number of iterations to converge, the proposed algorithms are suitable to practical applications.

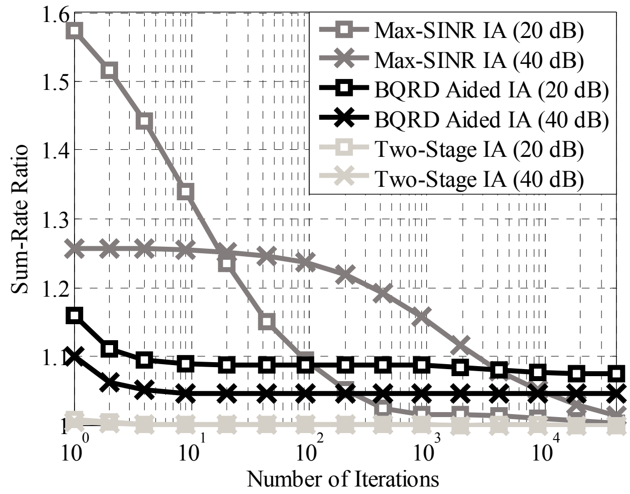

Figure 4–7: Convergence behavior of two-stage IA, BQRD aided IA, and max-SINR IA in UL CoMP systems with $P_{\text{UPW}} = 20$ and 40 dB.

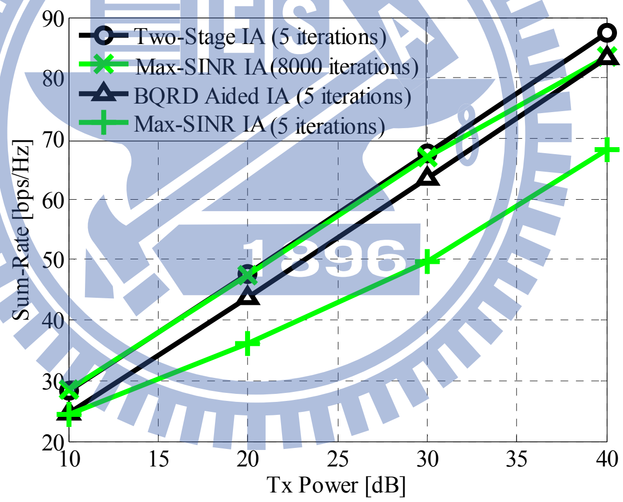

Figure 4–8: Sum-rate performance of two-stage IA, BQRD aided IA, and max-SINR IA in UL CoMP systems.

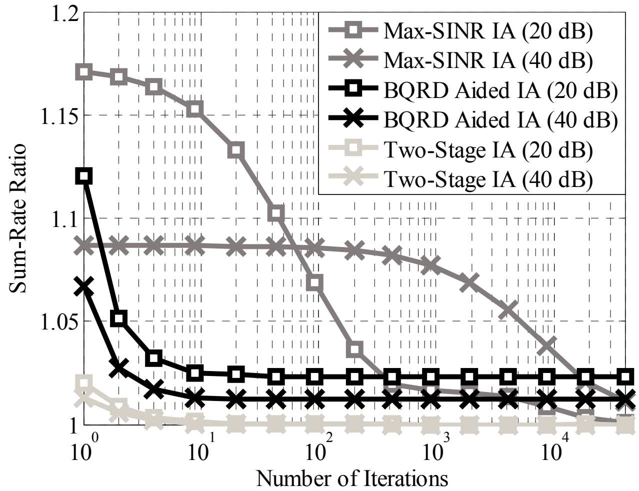

Figure 4–9: Convergence behavior of two-stage IA, BQRD aided IA, and max-SINR IA in UL CoMP systems with $P_{\text{UPW}} = 20$ and 40 dB in typical CoMP scenario.

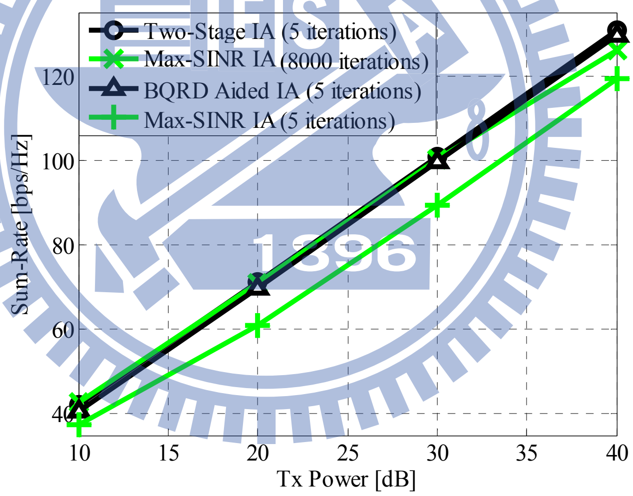

Figure 4–10: Sum-rate performance of two-stage IA, BQRD aided IA, and max-SINR IA in typical CoMP scenario.

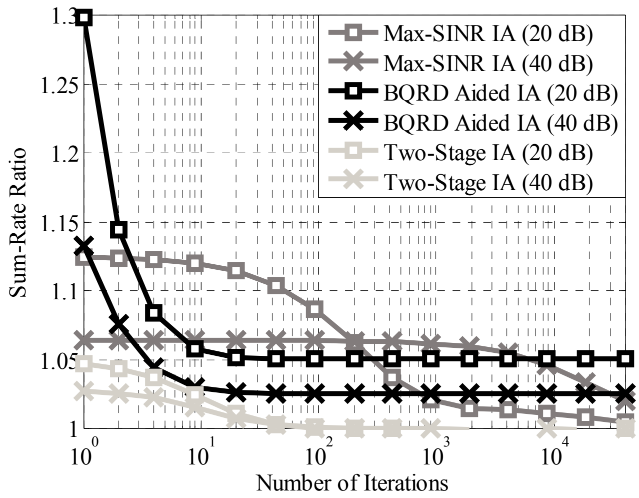

Figure 4–11: Convergence behavior of two-stage IA, BQRD aided IA, and max-SINR IA in UL CoMP systems with $P_{UPW} = 20$ and 40 dB in large CoMP size scenario.

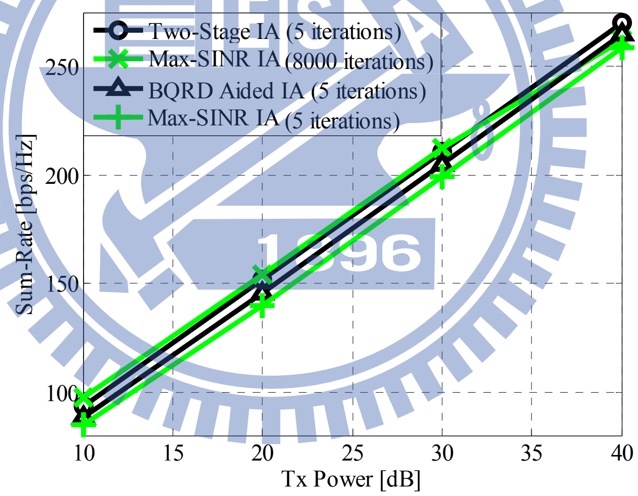

Figure 4–12: Sum-rate performance of two-stage IA, BQRD aided IA, and max-SINR IA in large CoMP size scenario.

Table 4-6: Complexity reduction ratio of proposed algorithms in convergence

	Typical CoMP scenario	Large CoMP size scenario
BQRD aided IA	99.9237%	99.9284%
Two-stage IA	99.8079%	98.3352%

4.6 Summary

In this chapter, considering the implementation issue of convergence rate, two IA-aided transceiver design algorithms (i.e., the BQRD aided IA and two-stage IA) are proposed for UL CoMP systems in this chapter. Due to the interference pre-subtraction by the aid of BQRD, the convergence rate of the BQRD aided IA algorithm is boosted while having comparable performance to the max-SINR IA. On the other hand, the joint optimization problem can be solved more quickly because the two-stage IA algorithm directly optimizes the structure of the effective channel jointly with power allocation. Moreover, the two-stage IA algorithm provides nearly the same performance as the max-SINR IA algorithm. Simulation results confirm that the proposed algorithms exhibit significant improvements in the rate of convergence. In the sum-rate performance, the proposed algorithms with 5 iterations achieve nearly the same performance as the max-SINR IA algorithm with 8000 iterations, and have even better performance in interference dominating regime. Furthermore, the results show that the proposed algorithms are advantageous in practical circumstances where each BS requires the coordination of multiple CoMP groups simultaneously. Therefore, this thesis provides promising solutions for future wireless communication systems that incorporate CoMP techniques such as LTE-A.

Chapter 5

Conclusions and Future Works

To deal with severe interference due to high user density in 4G mobile networks, several techniques have been developed to serve more users with better link quality. Two key techniques, CoMP transmission and MIMO, are proposed to satisfy such demands. In this thesis, we are dedicated to enhancing the sum-rate performance of cellular networks. As well known, cell-edge users have worse link quality due to severe interference from other cells, so the centralized uplink CoMP system is considered for its ability to deal with inter-cell interference. To further enhance the sum-rate performance, IA is adopted to provide more DoFs. Despite the improved performance, numerous iterations are required for the max-SINR IA to converge. To tackle this problem, we propose two IA aided transceiver designs (i.e., the BQRD aided IA and two-stage IA). Simulation results confirm that both of our proposed algorithms not only have better convergence behavior but also achieve comparable performance to the max-SINR IA.

In Chapter 2, we give a review of the CoMP transmission and reception and descriptions of both downlink and uplink CoMP schemes in 3GPP LTE-A. Next, to provide more DoFs, the centralized uplink CoMP is considered and its system model is also expressed. Then, because of the similar ability of IA with CoMP, the concept of IA is discussed.

In Chapter 3, we first review the definition of DoFs from the perspective of information theory and signal processing. Next, we discuss the DoFs of some communication systems to show the potential of full cooperation at the receiver side and IA. Then, we explain why we choose to incorporate IA in uplink rather than downlink transmission. Finally, the modified minimum leakage-IA and maximum SINR-IA in centralized uplink CoMP are investigated. However, as shown in the simulation results, it is found that numerous iterations are required to achieve the improved sum-rate performance, which is time-consuming.

Based on the concept of CoMP with IA schemes in the previous chapter, two new IA-aided transceiver designs are proposed in Chapter 4. One is the BQRD aided IA, which successfully breaks the interdependency between users. To further minimize the performance gap at low SNR, we propose the two-stage IA, which mitigates different kinds of interference separately and employs power loading. The reason is that we attempt to preserve available DoFs when defeating inter-user interference. From the simulation results, the proposed algorithms are shown to achieve improved performance in mitigating severe interference in CoMP scenarios with few iterations. Requiring only a small number of iterations to converge, the proposed algorithms are suitable to practical applications.

There are still some works worthy of future investigation. The first one is that some CSI imperfections can be addressed when designing the IA schemes, such as quantization errors and delayed CSI due to the limited backhaul mechanisms. The second one is that the configuration (i.e., the number of transmitted layers of each user) is pre-defined when evaluating decoders and precoders. To our knowledge, there has been no research addressing the question of whether the configurations is the best for channels. To achieve potential sum-rate performance of each channel, how to determine the best system configuration can be taken into consideration.

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