# 於上行多點協調式系統中基於編碼簿之高效率干擾校齊

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## 摘要

在行動蜂巢式通訊系統中，採用干擾校齊技術(interference alignment; IA)於上行多點協調式(coordinated multipoint; CoMP)系統可有效的提升系統效能。在本論文中，吾人提出基於編碼簿且使用最大訊號干擾雜訊比(max signal to interference and noise ratio; Max-SINR)演算法之高效率干擾校齊，並應用於接收端全合作之上行多點協調式系統。相對於傳統干擾校齊，基於編碼簿之干擾校齊只需要使用較少的資料回饋量即可顯著增進系統容量。為了在基於編碼簿之干擾校齊中避免窮舉式預編碼搜尋，吾人提出高效率之 $K$-Best 預編碼搜尋方法。為了進一步提升基於編碼簿之干擾校齊的效能，吾人提出階層式相位擴展法擴充現有的編碼簿。經由模擬結果的驗證，吾人提出之基於編碼簿之高效率干擾校齊可有效的提升傳統 CoMP 系統效能。

# Codebook Based Efficient Interference Alignment in Uplink Coordinated Multipoint Systems

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## Abstract

Adopting the interference alignment (IA) technique in uplink coordinated multipoint (CoMP) can improve the performance in mobile cellular systems. In this thesis, an efficient codebook-based Max-SINR IA aided uplink CoMP scheme with full cooperation at the receiver is proposed. Compared to conventional IA, codebook-based IA requires less feedback information and maintains the same significant improvement in system capacity. To avoid the exhaustive precoder search in codebook-based IA, the *K*-Best selection algorithm is adopted to efficiently perform precoder selection. To further improve the performance of codebook-based IA, we propose a layer-wise phase extension method for extending the existing codebook. Simulation results demonstrate that the proposed codebook-based IA and *K*-Best precoder selection algorithm can achieve a significant sum-rate performance gain over conventional CoMP.

# Acknowledgement

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# Acronym Glossary

| | |
|---|---|
| 3GPP | third generation partnership project |
| BS | base station |
| CA | carrier aggregation |
| CSI | channel state information |
| CoMP | coordinated multipoint |
| DL | downlink |
| DoF | degree of freedom |
| IA | interference alignment |
| ICI | inter cell interference |
| LTE | long term evolution |
| MIMO | multiple input multiple output |
| OFDMA | orthogonal frequency division multiple access |
| RRH | remote radio head |
| SC-FDMA | single carrier frequency division multiple access |
| SISO | single input single output |
| SDA | sphere decoding algorithm |
| SNR | signal to noise ratio |
| SINR | signal to interference and noise ratio |
| UE | user equipment |
| UL | uplink |

# Notations

| | |
|---|---|
| $M$ | total number of base stations |
| $P$ | total number of users |
| $N_t$ | number of transmit antennas |
| $N_r$ | number of receive antennas |
| $\mathbf{V}$ | precoder matrix |
| $\mathbf{U}$ | decoder matrix |
| $\mathbf{H}$ | channel matrix |
| $\mathbf{F}$ | equalizer matrix |
| $\mathbf{z}$ | noise vector |
| $\mathbf{x}$ | transmitted signal vector |
| $\mathbf{y}$ | received signal vector |
| $d$ | dimension of transmitted signal layers |
| $C$ | channel capacity |
| $P_w$ | transmit power |
| $R$ | achievable rate |
| $\gamma$ | SNR at the receiver |
| $E\{\bullet\}$ | expectation operator |
| $(\bullet)^H$ | conjugate transpose operator |
| $(\bullet)^T$ | transpose operator |
| $(\bullet)^{-1}$ | inverse operator |
| $\mathbf{X}^{(i)}$ | the $i$th column of matrix $\mathbf{X}$ |
| $\{\mathbf{X}\}_i^j$ | the $i$th column to the $j$th column of matrix $\mathbf{X}$ |

# Chapter 1

# Introduction

Long-Term Evolution (LTE) is the next generation mobile communication systems developed by Third Generation Partnership Project (3GPP), and is expected to provide users with high data rate services including video, audio, data, and voice signals [1]-[2]. The rapidly growing demands for these services drive the wireless communication technologies towards higher data rate, higher mobility, and higher link quality. However, severe interference, precious bandwidth resource, and limited transmit power make the design of next generation wireless communication systems extremely challenging. Hence, many innovative techniques have been developed in LTE to improve system capacity, link reliability, and spectral efficiency. For example, orthogonal frequency division multiple access (OFDMA), single carrier frequency division multiple access (SC-FDMA), and multiple-input multiple-output (MIMO) are some essential techniques in LTE. To further boost the system performance as required in LTE-Advanced (LTE-A), advanced techniques such as enhanced MIMO, carrier aggregation (CA) and coordinated multipoint (CoMP) have been developed [3]-[4].

CoMP has been adopted in LTE-A to improve cell average and cell edge throughputs [5]-[8]. It utilizes the cooperation between points in some cooperation group to coordinate the transmission for inter-cell interference (ICI) alleviation and link quality enhancement. According to cooperating types, CoMP can be classified into centralized and distributed CoMP. Centralized CoMP with joint transmission and reception is a full cooperation approach involving the exchange of information such as full channel state information (CSI) and full data information. Full cooperation scheme is applicable with less backhaul constraints as in cooperation between base station (BSs) and remote radio heads (RRHs) in LTE-A. On the other hand, distributed CoMP is a partial cooperation approach which exchanges partial CSI and partial data [8].

Interference alignment (IA) has recently been proposed as an effective interference resistant technique in *K*-user channels [9]-[12]. The basic idea of IA is to align or compress the interference into some limited subspaces by iterative precoder and decoder design, so that the interference can be separated from the desired signal. According to different schemes of precoder and decoder design, IA can be classified into distributed and centralized IA. Distributed IA performs iterations between BSs and user equipments (UEs) to compute the corresponding IA precoder and decoder. In centralized IA, the iterative procedure is instead performed in a dedicated central processer. IA can be adopted in either uplink (UL) or downlink (DL) CoMP to enhance the suppression of multiuser interference. In this thesis, IA aided UL centralized CoMP is considered because it requires less overhead for information exchange than the DL case.

In UL centralized CoMP systems, cooperating BSs forward received signals and CSI to a central processor which then computes the corresponding IA precoder and decoder jointly [13]-[14]. Therefore, the central processor needs to feed back the exact IA precoder matrix to each UE, which is inefficient and impractical. As a remedy, we propose a codebook-based IA scheme which feeds back only the precoder matrix index instead of the matrix itself.

To further reduce the computational load in searching the optimal precoder, we adopt the $K$-Best precoder search algorithm [15]-[16] to efficiently perform precoder selection in the codebook-based IA. The concept of $K$-Best search was originally introduced in the sphere decoding algorithm (SDA) for MIMO detection. A $K$-Best SDA uses breadth-first search and keeps the $K$ best candidates at each layer for the next layer search, thereby maintaining a lower complexity than conventional SDA [16]. After solving the computational load problem, we attempt to further improve the performance of codebook-based IA by adopting several codebook extension methods. Conventional extension methods can be classified into scale extension method and phase extension method [17]-[18]. We here propose a new layer-wise phase rotation method to further improve the performance of phase extension.

The remainder of the thesis is organized as follows. The system model is illustrated in Chapter 2. The adopted IA algorithm and the proposed codebook-based IA are introduced in Chapter 3. The efficient $K$-Best precoder search method and several effective codebook extension methods are introduced In Chapter 4. Chapter 5 gives concluding remarks of this thesis and leads the way to some potential works.

# Chapter 2

# System Model

The CoMP technique utilizes the cooperation between points in some cooperation group to coordinate the transmission for ICI alleviation and link quality enhancement. According to cooperating types, CoMP can be classified into centralized and distributed CoMP. In Section 2.1, we introduce the centralized UL CoMP system which is a full cooperation approach involving the exchange of information such as full CSI and full data information. The full cooperation scheme is applicable with less backhaul constraint as in cooperation between base stations and remote radio heads. In LTE-A heterogeneous networks (CoMP scenario 3 and 4) [5], macro and micro cells operate at different transmission power levels and achieve fast transfer of signal and channel information over dedicated fiber. The central BS (macro cell BS) collects information from each RRH (micro cell BS) and decodes the signal jointly as shown in Figure 2-1. Since the CoMP and IA techniques are dedicated to improving the performance of the system capacity, we introduce MIMO system capacity and the achievable sum-rate analysis in Section 2.2. In Section 2.3, the recently emerged IA technique for *K*-user interference system is introduced. The basic idea of IA is to align the interference into some limited dimension subspaces by iterative precoder and decoder design, so the interference can be separated from the desired signal. In order to improve the CoMP system performance by effective IA technique, we introduce the centralized IA in UL

CoMP systems in Section 2.4. In centralized IA, the iterative precoder and decoder design procedure is performed in a dedicated central processor instead of iterative design between BSs and UEs. A summary of Chapter 2 is given in Section 2.5.

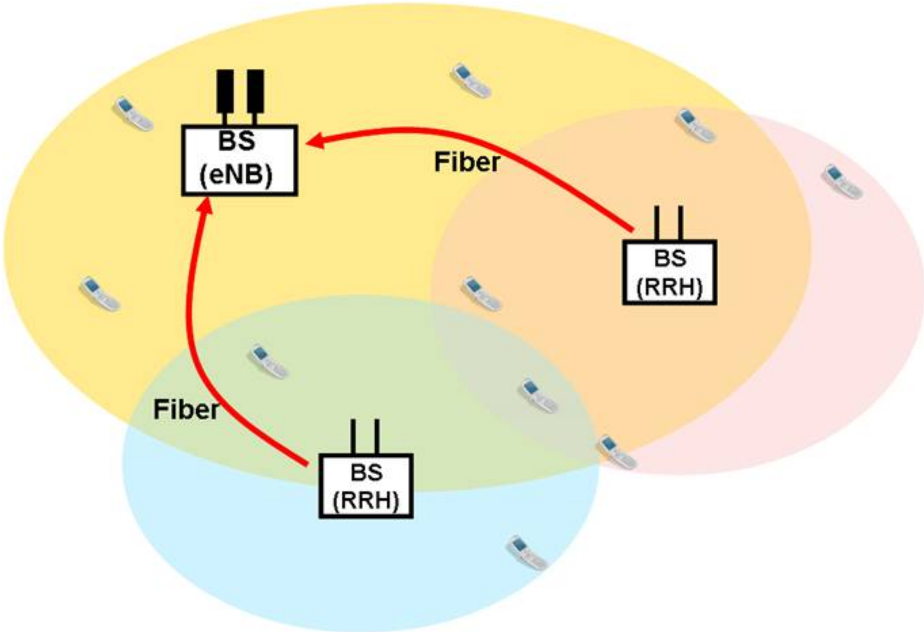


**Figure 2-1**: Centralized UL CoMP systems in heterogeneous networks

## 2.1 Uplink Coordinated Multipoint (CoMP) System Model

In this section, the centralized UL CoMP MIMO system model is introduced. The UL CoMP system involves $M$ BSs ($M$ cells), each equipped with $N_r$ antennas. As shown in Figure 2-2, each BS connects to $P$ UEs equipped with $N_t$ antennas. The transmitted signal vector $\mathbf{x}_m^p \in \mathbb{C}^{d_m \times 1}$ of the $p$th UE in the $m$th BS (main cell) is processed by the precoder matrix $\mathbf{V}_m^p \in \mathbb{C}^{N_t \times d_m}$. The channel matrix between the $p$th UE in the $l$th cell and the $m$th BS is denoted as $\mathbf{H}_{m,l}^p \in \mathbb{C}^{N_r \times N_t}$. The received signal at the $m$th BS can be described 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 total transmit dimension of signal layers in the $l$th cell can be formulated as $P \times d_l$, so the total transmit dimension of the system is formulated as $d_T = \sum_{l=1}^{M} P \times d_l$. Thus, the transmit signal at the $l$th cell is denoted as $\mathbf{x}_l = [(\mathbf{x}_l^1)^T, (\mathbf{x}_l^2)^T, \ldots, (\mathbf{x}_l^P)^T]^T \in \mathbb{C}^{(Pd_l)\times 1}$. Precoder matrix at the $l$th cell is denoted as $\mathbf{V}_l = \mathrm{diag}\{[\mathbf{V}_l^1, \ldots, \mathbf{V}_l^P]\} \in \mathbb{C}^{N_t P \times d_l P}$. The channel matrix between the $m$th BS and all UEs in the $l$th cell are denoted as $\mathbf{H}_{m,l} \in \mathbb{C}^{N_r \times N_t P}$ and the $m$th BS noise vector is denoted as $\mathbf{z}_m \in \mathbb{C}^{N_r \times 1}$ with distribution $CN(\mathbf{0}, N_0\mathbf{I}_{N_r})$.

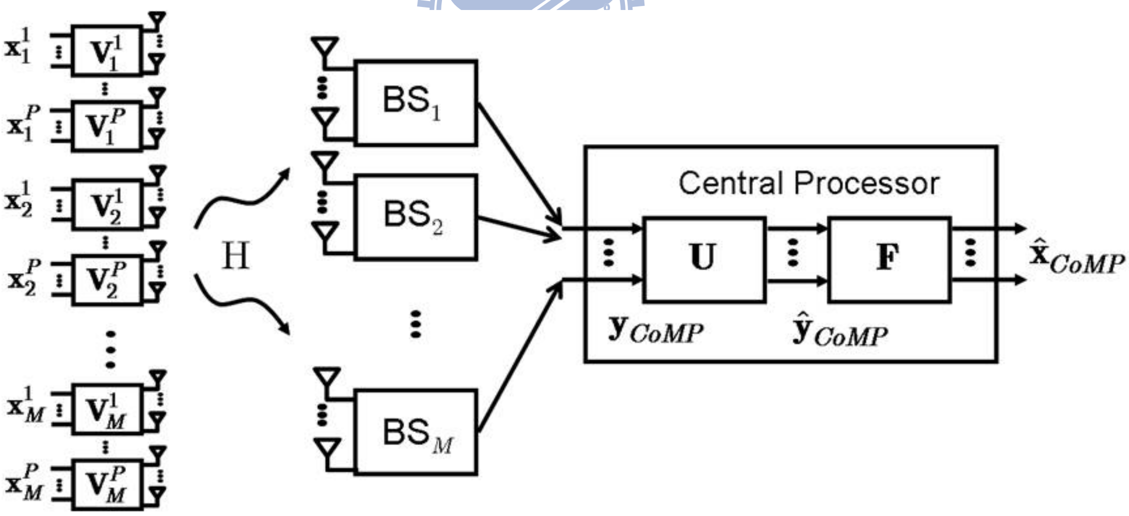


**Figure 2-2**: Illustration of UL centralized CoMP system model

In centralized CoMP, cooperation between BSs is available. As shown in Figure 2-2, the received signal from all BSs collected by the central processor (one of the BSs) can be formulated as

$$\mathbf{y}_{\text{CoMP}} = \mathbf{HVx} + \mathbf{z}, \tag{2.2}$$

where $\mathbf{x} = [\mathbf{x}_1^T, \mathbf{x}_2^T, \ldots, \mathbf{x}_M^T]^T \in \mathbb{C}^{d_T \times 1}$ is the aggregated transmitted signal. $\mathbf{V} = \text{diag}\{[\mathbf{V}_1, \ldots, \mathbf{V}_M]\} \in \mathbb{C}^{N_t PM \times d_T}$ is the aggregated precoder matrix, $\mathbf{H} \in \mathbb{C}^{N_r M \times N_t PM}$ is the aggregated channel matrix, and $\mathbf{z} = [\mathbf{z}_1^T, \mathbf{z}_2^T, \ldots, \mathbf{z}_M^T]^T \in \mathbb{C}^{(N_t M) \times 1}$ is the aggregated noise vector.

The central processor then processes the received signal as follows:

$$\hat{\mathbf{y}}_{\text{CoMP}} = \mathbf{U}^H \mathbf{HVx} + \mathbf{U}^H \mathbf{z}, \tag{2.3}$$

$$\hat{\mathbf{x}}_{\text{CoMP}} = \mathbf{F}^H \mathbf{U}^H \mathbf{HVx} + \mathbf{F}^H \mathbf{U}^H \mathbf{z}, \tag{2.4}$$

where $\hat{\mathbf{x}}_{\text{CoMP}}$ is the estimated signal, and $\mathbf{U}^H \in \mathbb{C}^{d_T \times N_r M}$ is the joint decoder matrix. It follows that the equivalent channel matrix $\mathbf{H}_{eff} \in \mathbb{C}^{d_T \times d_T}$ and the equalizer matrix $\mathbf{F}^H \in \mathbb{C}^{d_T \times d_T}$ can be expressed as follows:

$$\mathbf{H}_{eff} = \mathbf{U}^H \mathbf{HV}, \tag{2.5}$$

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

## 2.2 Channel Capacity

Channel capacity is the highest rate in bits per channel use at which information can be transmitted with an arbitrary probability of error. We introduce the single-input-single-output (SISO) channel capacity and then introduce the capacity of the MIMO channel. The channel capacity is defined as [19]

$$C = \max_{p(x)} \mathrm{I}(X;Y), \tag{2.7}$$

where

$$\mathrm{I}(X;Y) = H(Y) - H(Y \mid X), \tag{2.8}$$

where $\mathrm{I}(X;Y)$ is the mutual information between $X$ and $Y$, $H(Y)$ and $H(Y \mid X)$ are the differential entropy of $Y$ and differential conditional entropy of $Y$ with knowledge of $X$ given.

The ergodic capacity of a SISO system with a random complex channel gain $h$ can be formulated as [19]

$$C = E\left[\log_2(1 + \gamma |h|^2)\right], \tag{2.9}$$

where $\gamma = P_w / N_0$ is the SNR at the receiver, $P_w$ is the transmit power and $E\{\cdot\}$ denotes the expectation over all channel realization. For a MIMO system with $N_t$ transmit antennas and $N_r$ receive antennas, the capacity of a random complex MIMO channel is given by

$$C = \max_{tr(\mathbf{R}_{xx}) = N_t} E\left\{\log_2\left[\det\left(\mathbf{I}_{N_r} + \frac{P_w}{N_o N_t}\mathbf{H}\mathbf{R}_{xx}\mathbf{H}^H\right)\right]\right\}, \tag{2.10}$$

where $\mathbf{R}_{xx} = E\left\{\mathbf{x}\mathbf{x}^H\right\}$ is the covariance matrix of the transmitted signal vector $\mathbf{x}$. The covariance matrix of the transmitted signal can be formulated as $\mathbf{R}_{xx} = \mathbf{I}_{N_r}$ because the signal are assumed to be independent and unit-power. As a result, the ergodic capacity of a MIMO system can be formulated as

$$C = E\left\{\log_2\left[\det\left(\mathbf{I}_{N_r} + \frac{P_w}{N_o N_t}\mathbf{H}\mathbf{H}^H\right)\right]\right\}. \tag{2.11}$$

As a performance index of the CoMP system in the previous section, we adopt the

MIMO capacity formula in the level of each transmitted signal layers. The achievable rate at each layer can be formulated as [20]

$$R_d = E\left[\log_2\left(1 + \mathrm{SINR}_d\right)\right], \tag{2.12}$$

where the $\mathrm{SINR}_d$ is given by

$$\frac{\mathbf{F}^{(d)}\mathbf{H}_{eff}^{(d)}\mathbf{H}_{eff}^{(d)H}\mathbf{F}^{(d)H}}{\sum_{l \neq d} \mathbf{F}^{(d)}\mathbf{H}_{eff}^{(l)}\mathbf{H}_{eff}^{(l)\,H}\mathbf{F}^{(d)H} + \mathbf{F}^{(d)}\mathbf{U}N_0\mathbf{U}^H\mathbf{F}^{(d)H}}, \tag{2.13}$$

where $N_0$ is the noise variance, $\mathbf{F}^{(d)} \in \mathbb{C}^{1 \times d_T}$ is the equalizer matrix for the *d*th layer, and $\mathbf{H}_{eff}^{(d)} \in \mathbb{C}^{d_T \times 1}$ is the equivalent channel matrix for the *d*th layer. The achievable sum-rate of all layers can be expressed as

$$R_{sum} = \sum_{d=1}^{d_T} E\left[\log_2\left(1 + \mathrm{SINR}_d\right)\right], \tag{2.14}$$

where $d_T = \sum_{l=1}^{M} P \times d_l$ is the total dimension of the transmitted signal layers.

## 2.3 Interference Alignment

Interference alignment (IA) has recently been proposed as an effective interference resistant technique in several systems such as X-channel, *K*-user interference channel, and the CoMP system. As shown in Figure 2-3, the basic idea of IA is to align or compress interference into some limited subspace, so the interference can be separated from the desired signal with sufficient degrees of freedom (DoF). The DoF can be provided by several ways, such as multiple antennas, frequency, time, or phase. Since the MIMO techniques are rapidly developed in the communication systems, providing the DoF by multi-antenna transmission is the most practical way.

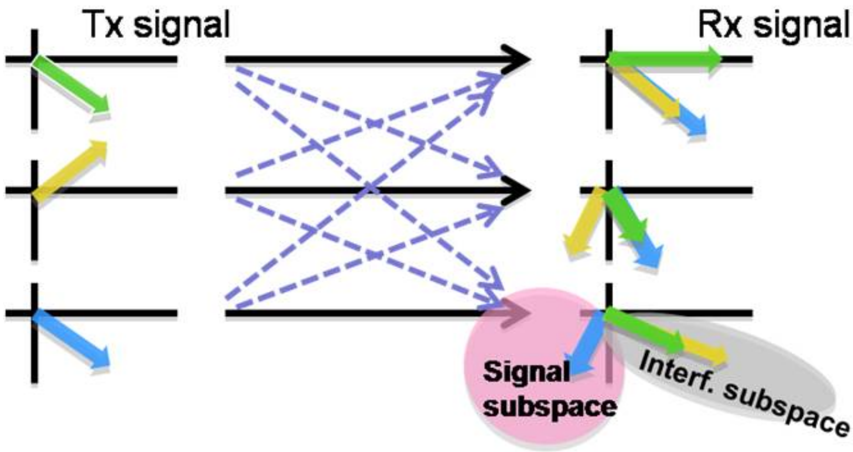


**Figure 2-3**: Illustration of basic IA concept

Considering $K$-user interference system as shown in Figure 2-4 [9], there are $K$ BSs and $K$ UEs in the system. Each BS and UE are equipped with $N_t$ and $N_r$ antennas respectively. The transmitted signal $\mathbf{x}_k$ from UE is intended for the $k$th BS. The main difference between UL CoMP system and the $K$-user system is that each BS processes its own received signal from the corresponding UE in $K$-user system while the central processor processes all received signal in UL CoMP system. The $k$th received signal and the $k$th estimated signal can be expressed as follows:

$$\hat{\mathbf{y}}_{\mathrm{k}} = \mathbf{U}_k^H \sum_{l=1}^{K} \mathbf{H}_{k,l} \mathbf{V}_l \mathbf{x}_l + \mathbf{U}_k^H \mathbf{z}_k, \tag{2.15}$$

$$\hat{\mathbf{x}}_{\mathrm{k}} = \mathbf{F}_k^H \mathbf{U}_k^H \sum_{l=1}^{K} \mathbf{H}_{k,l} \mathbf{V}_l \mathbf{x}_l + \mathbf{F}_k^H \mathbf{U}_k^H \mathbf{z}_k, \tag{2.16}$$

where $\mathbf{U}_k^H \in \mathbb{C}^{d_k \times N_r}$ and $\mathbf{F}_k^H \in \mathbb{C}^{d_k \times d_k}$ represent the $k$th decoder matrix and the $k$th equalizer matrix.

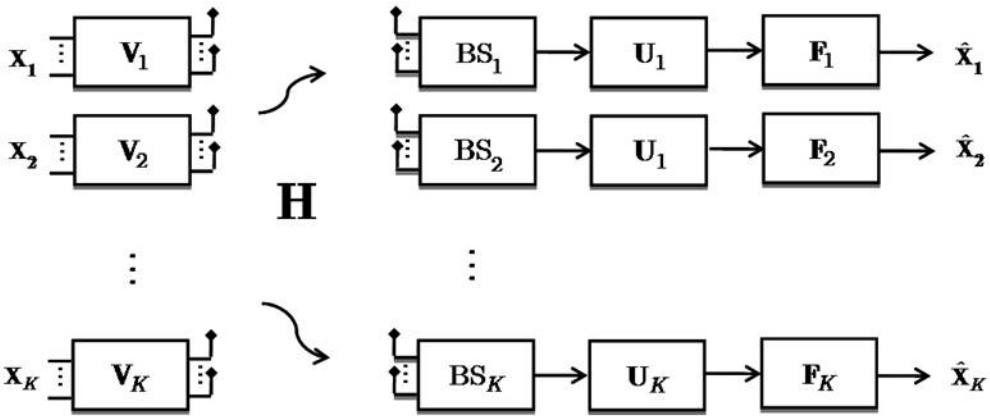


**Figure 2-4**: Illustration of *K*-user system model

In *K*-user interference channel, IA has been proved to be a capacity achieving approach which aligns the interference into some limited subspace so there would be some residual DoF for the desired signal. Based on these opinions, the IA design criterion in *K*-user system is given as follows [9] (taking the $k$th BS for example):

$$\mathbf{U}_k^H \mathbf{H}_{k,l} \mathbf{V}_l = 0, \ \forall l \neq k, \tag{2.17}$$

$$\mathrm{rank}(\mathbf{U}_k^H \mathbf{H}_{k,k} \mathbf{V}_k) = d_k, \tag{2.18}$$

where the Equation (2.17) and (2.18) express that at each receiver, all interference is suppressed, leaving as many interference-free dimensions as the degrees of freedom by proper precoder and decoder design.

According to different schemes of precoder and decoder design, IA can be classified into distributed and centralized IA. In distributed IA, the design starts with an arbitrary precoder and which induced an optimal decoder at receiver side and then this decoder triggers a specific algorithm to update the precoder. As shown in Figure 2-5, the distributed IA algorithm goes back and forth between BSs and UEs to attain interference suppression. Different from distributed IA, the centralized IA performs iterative computing in a central processor. The central processor collects all channel information and computes the decoder with an arbitrary precoder and then updates the precoder with a specific algorithm. Thus the centralized IA is more practical for mobile cellular communications such as CoMP systems.

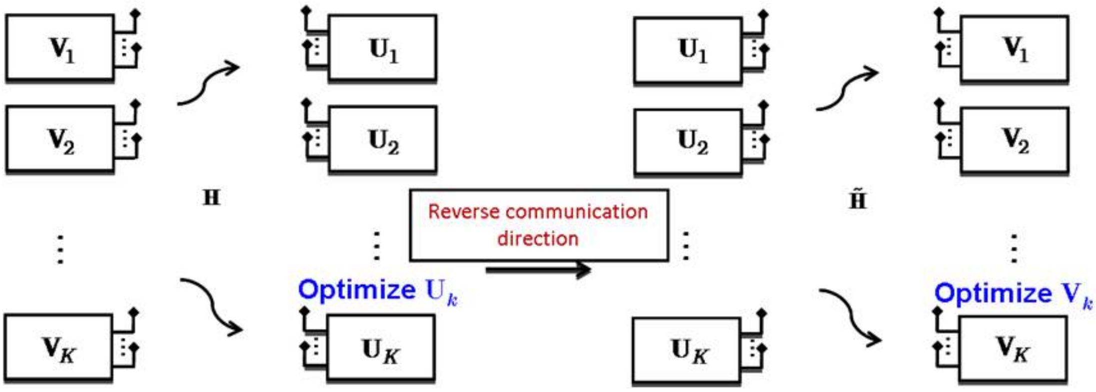


**Figure 2-5**: Illustration of the distributed IA in *K*-user system

## 2.4 Interference Alignment in Uplink CoMP System

In this section, the centralized IA technique in UL CoMP system is introduced. The basic idea of IA in UL CoMP system is to align the interference into some other subspaces by iterative precoder and joint decoder design. In UL CoMP system with IA technique, a central processor collects channel information and all of the received signal to compute the precoder and joint decoder which satisfied the IA design criterion. For simplicity, we assume that a single UE ($P = 1$) is involved in each coordinated cell for CoMP operation as Figure 2-6 shown. The design criterion of IA in UL CoMP at the $m$th BS $\forall m \in \{1, 2, \ldots, M\}$ can be reformulated as

$$\left(\{\mathbf{U}\}_{(m-1)d_m+1}^{m\times d_m}\right)^H \mathbf{H}_l \{\mathbf{V}\}_{(m-1)d_m+1}^{m\times d_m} = 0, \quad \forall l \neq m, \tag{2.19}$$

$$\operatorname{rank}\left(\left(\{\mathbf{U}\}_{(m-1)d_m+1}^{m\times d_m}\right)^H \mathbf{H}_l \{\mathbf{V}\}_{(m-1)d_m+1}^{m\times d_m}\right) = d_m, \tag{2.20}$$

where $\mathbf{U}$ is the joint decoder matrix, $\mathbf{V}$ is the diagonal precoder matrix, and $\mathbf{H}_l = [\mathbf{H}_{1,l}^T, \mathbf{H}_{2,l}^T, \ldots, \mathbf{H}_{M,l}^T]^T$ is the aggregated channel matrix.

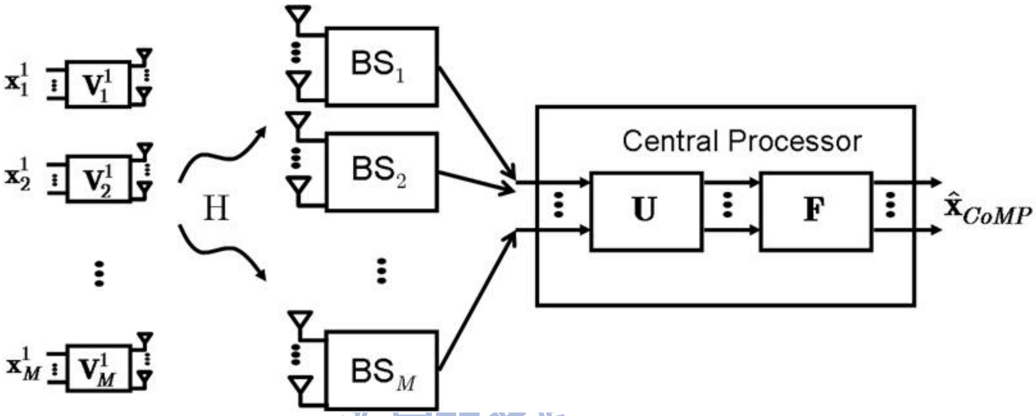


**Figure 2-6**: Illustration of UL centralized CoMP with a single UE in a coordinated cell

IA can be adopted in either uplink or downlink CoMP to enhance the suppression of multiuser interference. As shown in Figure 2-7, the main difference between IA in UL and DL CoMP is that the UL CoMP system requires less overhead for information exchange than in the DL case. In DL CoMP system, the BS transmits the signal to each UE which needs to feed back the CSI to the BS. Then, BS computes the corresponding decoder and sends to the UE. In UL case, the UE transmits the signal to the BS which estimates the channel information and computes the joint decoder and the corresponding precoder for each UE. After the IA precoder and decoder computation, the BS only needs to feed back the corresponding precoder to each UE.


**Figure 2-7**: Illustration of information exchange with IA in DL and UL CoMP cases

## 2.5 Summary

In this chapter, we give a review of UL centralized CoMP systems. In centralized CoMP, the full cooperation between BSs is available. The received signal and the channel information from all BSs are collected by the central processor which decodes the signal jointly. As the performance index, we introduce the MIMO system capacity and the achievable sum-rate of all the transmitted signal layers. We also introduce the IA concept and corresponding IA precoder and decoder design criterion in $K$-user systems. According to different schemes of precoder and decoder design, IA can be classified into distributed and centralized IA. In view of the interference resistant ability of IA, we adopt the centralized IA and reformulate the IA design criterion in UL CoMP systems.

# Chapter 3

# Codebook Based Interference Alignment in Uplink CoMP Systems

In this chapter, the IA algorithms and the proposed codebook-based IA in UL CoMP systems are introduced. In Section 3.1, Motivations of the codebook-based IA with Max-SINR algorithm are introduced. Various popular approaches of IA algorithm in UL CoMP systems such as minimum leakage (Min-leakage) IA and maximum SINR (Max-SINR) IA are reformulated in Section 3.2. To implement the IA technique in UL CoMP systems, the codebook-based IA in UL CoMP systems is proposed in Section 3.3. The computer simulations are exhibited in Section 3.4. A summary of Chapter 3 is given in Section 3.5.

## 3.1 Motivation

In order to further improve the performance of UL CoMP technique which has been adopted in LTE-A to improve cell average and cell edge throughputs, we adopt IA technique in UL CoMP systems. Various popular approaches of the IA algorithm such as Min-leakage IA and Max-SINR IA have been developed to achieve the goals of IA. The Min-leakage IA is dedicated to suppress the interference at each receiver but it makes no attempt to maximize the desired signal power within the desired signal subspace. Hence, we adopt the alternative Max-SINR algorithm, in which the precoder and joint decoder are designed iteratively to maximize per layer SINR.

To implement the IA algorithm in centralized UL CoMP systems, the central processor needs to send the corresponding precoder matrix to each UE. However, in practice, the feedback information is limited by the capacity of the control channels, hence making it inefficient to send the exact IA precoder matrix to each UE. In order to reduce the amount of feedback information, the codebook-based IA in UL CoMP systems is proposed.

## 3.2 Interference Alignment Algorithms

Following the Equation (2.19), (2.20), and the UL CoMP system model in Section 2.4, the design criterion of IA in UL CoMP at the $m$th BS $\forall m \in \{1,2,\ldots,M\}$ is given as follows:

$$\left(\{\mathbf{U}\}_{(m-1)d_m+1}^{m\times d_m}\right)^H \mathbf{H}_l \{\mathbf{V}\}_{(m-1)d_m+1}^{m\times d_m} = 0, \ \forall l \neq m, \tag{3.1}$$

$$\operatorname{rank}\left(\left(\{\mathbf{U}\}_{(m-1)d_m+1}^{m\times d_m}\right)^H \mathbf{H}_l \{\mathbf{V}\}_{(m-1)d_m+1}^{m\times d_m}\right) = d_m, \tag{3.2}$$

where $\mathbf{U}$ is the joint decoder matrix, $\mathbf{V}$ is the diagonal precoder matrix, and $\mathbf{H}_l = [\mathbf{H}_{1,l}^T, \mathbf{H}_{2,l}^T, \ldots, \mathbf{H}_{M,l}^T]^T \in \mathbb{C}^{N_r M \times N_t}$ is the aggregated channel matrix. The quality of interference alignment is typically measured by the leakage power of the receiver. Along this line, the basic iterative Min-leakage IA algorithm aims at minimizing the total leakage interference, whose criterion at the $m$th cell can be formulated as follows [9]:

$$\min_{\mathbf{U}} \operatorname{tr}\left(\left(\{\mathbf{U}\}_{(m-1)d_m+1}^{m\times d_m}\right)^H \mathbf{Q}_m \{\mathbf{U}\}_{(m-1)d_m+1}^{m\times d_m}\right), \tag{3.3}$$

$$\mathbf{Q}_m = \sum_{l \neq m} \mathbf{H}_l \mathbf{V}_l \mathbf{V}_l^H \mathbf{H}_l^H, \tag{3.4}$$

which yields the decoder matrix

$$\mathbf{U}^{((m-1)d_m+d)} = \mathrm{eig}_d \left[\mathbf{Q}_m\right], \tag{3.5}$$

$\forall m \in \{1,2,\ldots,M\}$, where $\mathrm{eig}_d\left[\mathbf{X}\right]$ represent the eigenvector corresponding to the $d$th smallest eigenvalue of $\mathbf{X}$. We can obtain the optimal precoder in the central processor by minimize total interference leakage at the UE in the $m$th cell. The Min-leakage algorithm of the precoder design can be formulated as follows:

$$\min_{\mathbf{V}} \mathrm{tr}\left((\mathbf{V})_m^H \tilde{\mathbf{Q}}_m (\mathbf{V})_m\right), \tag{3.6}$$

$$\tilde{\mathbf{Q}}_m = \sum_{l \neq m} \mathbf{H}_l^H \{\mathbf{U}\}_{(l-1)d_m+1}^{l \times d_m} \left(\{\mathbf{U}\}_{(l-1)d_m+1}^{l \times d_m}\right)^H \mathbf{H}_l, \tag{3.7}$$

which yields the precoder matrix

$$\mathbf{V}_m^{(d)} = \mu \cdot \mathrm{eig}_d\left[\tilde{\mathbf{Q}}_m\right], \tag{3.8}$$

where $\mu$ is chosen to satisfy $\mathrm{tr}(\mathbf{V}_m \mathbf{x}_m \mathbf{x}_m^H \mathbf{V}_m^H) = P_w$ and $\mathbf{x}_m$ is denoted as the transmitted signal. The steps of Min-leakage IA algorithm can be summarized as follows:

Step 1.

Start with an arbitrary precoder $\mathbf{V}_m$, $\forall m \in \{1,2,\ldots,M\}$.

Step 2.

Compute the optimal decoder $\mathbf{U}^{((m-1)d_m+d)}$ using Equation (3.5) with obtained $\mathbf{V}_m$ from previous step, $\forall m \in \{1,2,\ldots,M\}$.

Step 3.

Compute the optimal precoder $\mathbf{V}_m$ using Equation (3.8) with obtained

$\mathbf{U}^{((m-1)d_m+d)}$ from previous step.

Step 4.

Iteratively process the step 2 and step 3 unless the number of iterations reaches a predefined value.

The goal of Min-leakage IA algorithm is to seek perfect interference suppression by progressively reducing the leakage interference. However, the Min-leakage IA makes no attempt to ensure the desired signal power within the desired signal subspace. Therefore, we adopt the alternative Max-SINR IA algorithm in this thesis.

The precoder and the joint decoder are designed iteratively to maximize the per layer SINR in Max-SINR IA algorithm. The Max-SINR IA $\forall m \in \{1,2,\ldots,M\}$, $\forall i \in \{1,2,\ldots,d_m\}$ can be formulated as follows:

$$\max_{\mathbf{U}} \frac{\mathbf{U}^{((m-1)d_m+i)H}\mathbf{H}_m\mathbf{V}^{((m-1)d_m+i)}\mathbf{V}^{((m-1)d_m+i)H}\mathbf{H}_m^H\mathbf{U}^{((m-1)d_m+i)}}{\mathbf{U}^{((m-1)d_m+i)H}\mathbf{B}_m^{(i)}\mathbf{U}^{((m-1)d_m+i)}}, \quad (3.9)$$

$$\text{subject to } \left(\{\mathbf{V}\}_{(m-1)d_m+1}^{m\times d_m}\right)^H \{\mathbf{V}\}_{(m-1)d_m+1}^{m\times d_m} = (P_w / d_m)\mathbf{I}_{d_m}, \quad \|\mathbf{U}\| = 1, \quad (3.10)$$

where $P_w$ is the transmit power. The interference plus noise term $\forall l \in \{1,2,\ldots,M\}$, $\forall i \in \{1,2,\ldots,d_T\}$ can be expressed as

$$\mathbf{B}_m^{(i)} = \sum_l \sum_d \mathbf{H}_l\mathbf{V}^{((l-1)d_m+d)}\mathbf{V}^{((l-1)d_m+d)H}\mathbf{H}_l^H - \mathbf{H}_m\mathbf{V}^{((m-1)d_m+i)}\mathbf{V}^{((m-1)d_m+i)H}\mathbf{H}_m^H + N_0\mathbf{I}, \quad (3.11)$$

which yields the decoder matrix

$$\mathbf{U}^{((m-1)d_m+i)} = \left(\mathbf{B}_m^{(i)}\right)^{-1}\mathbf{H}_m\mathbf{V}^{((m-1)d_m+i)} \Big/ \left\|\left(\mathbf{B}_m^{(i)}\right)^{-1}\mathbf{H}_m\mathbf{V}^{((m-1)d_m+i)}\right\|. \quad (3.12)$$

The optimal precoder matrix which is computed by maximize the per layer SINR in the central processor can be expressed as

$$\max_{\mathbf{V}} \frac{\mathbf{V}^{((m-1)d_m+i)H}\mathbf{H}_m^H\mathbf{U}^{((m-1)d_m+i)}\mathbf{U}^{((m-1)d_m+i)H}\mathbf{H}_m\mathbf{V}^{((m-1)d_m+i)}}{\mathbf{V}^{((m-1)d_m+i)H}\tilde{\mathbf{B}}_m^{(i)}\mathbf{V}^{((m-1)d_m+i)}}, \tag{3.13}$$

$$\text{subject to } \left(\{\mathbf{V}\}_{(m-1)d_m+1}^{m\times d_m}\right)^H \{\mathbf{V}\}_{(m-1)d_m+1}^{m\times d_m} = (P_w / d_m)\mathbf{I}_{d_m}, \quad \|\mathbf{U}\| = 1. \tag{3.14}$$

The interference plus noise term can be expressed as

$$\tilde{\mathbf{B}}_m^{(i)} = \sum_l \sum_d \mathbf{H}_l^H \mathbf{U}^{((l-1)d_m+d)}\mathbf{U}^{((l-1)d_m+d)H}\mathbf{H}_l - \mathbf{H}_m^H\mathbf{U}^{((m-1)d_m+i)}\mathbf{U}^{((m-1)d_m+i)H}\mathbf{H}_m + N_0\mathbf{I}, \tag{3.15}$$

which yields the optimal precoder matrix

$$\mathbf{V}^{((m-1)d_m+i)} = \left(\tilde{\mathbf{B}}_m^{(i)}\right)^{-1}\mathbf{H}_m^H\mathbf{U}^{((m-1)d_m+i)} \Big/ \left\|\left(\tilde{\mathbf{B}}_m^{(i)}\right)^{-1}\mathbf{H}_m^H\mathbf{U}^{((m-1)d_m+i)}\right\|. \tag{3.16}$$

The steps of iterative Max-SINR IA algorithm can be summarized as follows:

Step 1.

Start with the diagonal precoder $\mathbf{V}$ which is composed by arbitrary precoders in each UE, $\forall m \in \{1,2,\ldots,M\}$.

Step 2.

Compute interference plus noise term $\mathbf{B}_m^{(i)}$ by channel matrix and diagonal precoder matrix according to (3.11), $\forall l \in \{1,2,\ldots,M\}$, $\forall i \in \{1,2,\ldots,d_T\}$.

Step 3.

Compute the joint decoder $\mathbf{U}^{((m-1)d_m+i)}$ in the central processor according to Equation (3.12).

Step 4.

Reverse the computing direction and compute the interference plus noise term $\tilde{\mathbf{B}}_m^{(i)}$ by channel matrix and joint decoder matrix from previous step.

Step 5.

Compute the optimal precoder according to Equation (3.16).

Step 6.

Iteratively process the step 2 to step 5 unless the number of iterations reaches a predefined value.

Max-SINR IA algorithm has been proved to exhibit better sum-rate performance than Min-leakage IA [9]. This is due to that Max-SINR IA jointly considers the signal and interference to design the corresponding precoder and decoder.

## 3.3 Codebook Based Interference Alignment in Uplink CoMP Systems

To implement the IA algorithm in centralized UL CoMP systems, the central processor needs to send the corresponding precoder matrix to each UE. However, in practice, the feedback information is limited by the capacity of the control channels, hence making it inefficient to send the exact IA precoder matrix to each UE. In order to reduce the amount of feedback information, the codebook-based IA which adopt the existing codebook in LTE is proposed and illustrated in Figure 3-1.

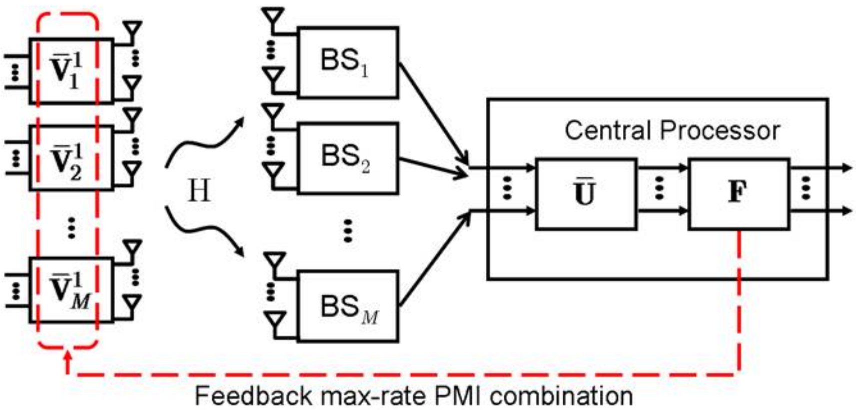


**Figure 3-1**: Illustration of codebook-based IA in centralized CoMP systems

Using the system model of Section 2.4, the diagonal precoder matrix composed by the codebook can be formulated as

$$\bar{\mathbf{V}} = \mathrm{diag}\left\{\left[\bar{\mathbf{V}}_1,\ldots,\bar{\mathbf{V}}_M\right]\right\}, \tag{3.17}$$

where $\bar{\mathbf{V}} \in \mathbb{C}^{N_t M \times d_T}$, $\bar{\mathbf{V}}_1,\ldots,\bar{\mathbf{V}}_M$ are chosen from the pre-defined LTE UL codebook $\mathbf{W}$ which are listed in Table 3-1 to Table 3-5 [15]. For each possible combination of precoder metrices, the central processor computes the corresponding decoder matrix using the Max-SINR algorithm $\forall m \in \{1,2,\ldots,M\}$, $\forall i \in \{1,2,\ldots,d_m\}$ is denoted as

$$\max_{\bar{\mathbf{U}}} \frac{\bar{\mathbf{U}}^{((m-1)d_m+i)H}\mathbf{H}_m\bar{\mathbf{V}}^{((m-1)d_m+i)}\bar{\mathbf{V}}^{((m-1)d_m+i)H}\mathbf{H}_m^H\bar{\mathbf{U}}^{((m-1)d_m+i)}}{\bar{\mathbf{U}}^{((m-1)d_m+i)H}\bar{\mathbf{B}}_m^{(i)}\bar{\mathbf{U}}^{((m-1)d_m+i)}}, \tag{3.18}$$

where the interference plus noise term can be formulated as

$$\begin{aligned}\bar{\mathbf{B}}_m^{(i)} &= \sum_l\sum_d \mathbf{H}_l\bar{\mathbf{V}}^{((l-1)d_m+d)}\bar{\mathbf{V}}^{((l-1)d_m+d)H}\mathbf{H}_l^H \\ &-\mathbf{H}_m\bar{\mathbf{V}}^{((m-1)d_m+i)}\bar{\mathbf{V}}^{((m-1)d_m+i)H}\mathbf{H}_m^H + N_0\mathbf{I},\end{aligned} \tag{3.19}$$

which yields the corresponding decoder matrix

$$\bar{\mathbf{U}}^{((m-1)d_m+i)} = \left(\bar{\mathbf{B}}_m^{(i)}\right)^{-1}\mathbf{H}_m\bar{\mathbf{V}}^{((m-1)d_m+i)} \Big/ \left\|\left(\bar{\mathbf{B}}_m^{(i)}\right)^{-1}\mathbf{H}_m\bar{\mathbf{V}}^{((m-1)d_m+i)}\right\|. \tag{3.20}$$

Since the precoders are selected from a finite set, the central processor only needs to send the precoder matrix index to each UE via a limited number of feedback bits. The steps of codebook-based IA with Max-SINR algorithm can be summarized as follows:

Step 1.

Start with precoders $\bar{\mathbf{V}}_m$ which are chosen from the codebook $\mathbf{W}$.

Step 2.

Central processor computes the corresponding joint decoder $\bar{\mathbf{U}}$ with all of the possible precoder combinations in the codebook.

Step 3.

Central processor computes the sum-rate of each precoder combination and the corresponding joint decoder.

Step 4.

After the sum-rate computation, the central processor feeds back the corresponding max-rate combination of precoder index to each UE.

**Table 3-1**: LTE UL codebook for 2 antennas

| Codebook index | No. of transmitted signal layers at each UE | |
|---|---|---|
| | No. of layers = 1 | No. of layers = 2 |
| 0 | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$ | $\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$ |
| 1 | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$ | |
| 2 | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$ | |
| 3 | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$ | |
| 4 | $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\end{bmatrix}$ | |
| 5 | $\frac{1}{\sqrt{2}}\begin{bmatrix}0\\1\end{bmatrix}$ | |

**Table 3-2**: LTE UL codebook for 4 antennas with no. of transmitted signal layers = 1

| Codebook index | No. of layers = 1 | | | |
|---|---|---|---|---|
| 0 - 3 | $\frac{1}{2}\begin{bmatrix}1\\1\\1\\-1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\1\\j\\j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\1\\-1\\1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\1\\-j\\-j\end{bmatrix}$ |
| 4 - 7 | $\frac{1}{2}\begin{bmatrix}1\\j\\1\\j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\j\\j\\1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\j\\-1\\-j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\j\\-j\\-1\end{bmatrix}$ |
| 8 - 11 | $\frac{1}{2}\begin{bmatrix}1\\-1\\1\\1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\-1\\j\\-j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\-1\\-1\\-1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\-1\\-j\\j\end{bmatrix}$ |
| 12 - 15 | $\frac{1}{2}\begin{bmatrix}1\\-j\\1\\-j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\-j\\j\\-1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\-j\\-1\\j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\-j\\-j\\1\end{bmatrix}$ |
| 16 - 19 | $\frac{1}{2}\begin{bmatrix}1\\0\\1\\0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\0\\-1\\0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\0\\j\\0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1\\0\\-j\\0\end{bmatrix}$ |
| 20 - 23 | $\frac{1}{2}\begin{bmatrix}0\\1\\0\\1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}0\\1\\0\\-1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}0\\1\\0\\j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}0\\1\\0\\-j\end{bmatrix}$ |

**Table 3-3**: LTE UL codebook for 4 antennas with no. of transmitted signal layers = 2

| Codebook index | No. of layers = 2 | | | |
|---|---|---|---|---|
| 0 - 3 | $\frac{1}{2}\begin{bmatrix}1 & 0\\1 & 0\\0 & 1\\0 & -j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\1 & 0\\0 & 1\\0 & j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\-j & 0\\0 & 1\\0 & 1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\-j & 0\\0 & 1\\0 & -1\end{bmatrix}$ |
| 4 - 7 | $\frac{1}{2}\begin{bmatrix}1 & 0\\-1 & 0\\0 & 1\\0 & -j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\-1 & 0\\0 & 1\\0 & j\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\j & 0\\0 & 1\\0 & 1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\j & 0\\0 & 1\\0 & -1\end{bmatrix}$ |
| 8 - 11 | $\frac{1}{2}\begin{bmatrix}1 & 0\\0 & 1\\1 & 0\\0 & 1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\0 & 1\\1 & 0\\0 & -1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\0 & 1\\-1 & 0\\0 & 1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\0 & 1\\-1 & 0\\0 & -1\end{bmatrix}$ |
| 12 - 15 | $\frac{1}{2}\begin{bmatrix}1 & 0\\0 & 1\\0 & 1\\1 & 0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\0 & 1\\0 & -1\\1 & 0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\0 & 1\\0 & 1\\-1 & 0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0\\0 & 1\\0 & -1\\-1 & 0\end{bmatrix}$ |

**Table 3-4**: LTE UL codebook for 4 antennas with no. of transmitted signal layers = 3

| Codebook index | No. of layers = 3 | | | |
|---|---|---|---|---|
| 0 - 3 | $\frac{1}{2}\begin{bmatrix}1 & 0 & 0\\1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0 & 0\\-1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\1 & 0 & 0\\0 & 0 & 1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\-1 & 0 & 0\\0 & 0 & 1\end{bmatrix}$ |

| | | | | |
|---|---|---|---|---|
| 4 - 7 | $\frac{1}{2}\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\\ 1 & 0 & 0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\\ -1 & 0 & 0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\ 1 & 0 & 0\\ 1 & 0 & 0\\ 0 & 0 & 1\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\ 1 & 0 & 0\\ -1 & 0 & 0\\ 0 & 0 & 1\end{bmatrix}$ |
| 8 - 11 | $\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\ 1 & 0 & 0\\ 0 & 0 & 1\\ 1 & 0 & 0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\ 1 & 0 & 0\\ 0 & 0 & 1\\ -1 & 0 & 0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 1 & 0 & 0\\ 1 & 0 & 0\end{bmatrix}$ | $\frac{1}{2}\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 1 & 0 & 0\\ -1 & 0 & 0\end{bmatrix}$ |

**Table 3-5**: LTE UL codebook for 4 antennas with no. of transmitted signal layers = 4

| Codebook index | No. of layers = 4 |
|---|---|
| 0 | $\frac{1}{2}\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$ |

## 3.4 Computer Simulations

In this section, we simulate the sum-rate performance of the Max-SINR IA in UL CoMP systems, proposed codebook-based IA method in UL CoMP systems, and the conventional CoMP system with multiplexing. For the simulation configuration as shown in Figure 3-2, we consider three BSs in the cooperation group and one UE in coverage of each BS ($M$ = 3, $P$ = 1). The channel matrices are assumed i.i.d. complex Gaussian with a unit variance. Each BS is equipped with $N_r$ antennas and each UE is equipped with $N_t$ antennas. We also assume that all UEs transmit with same number of signal layers i.e. $d_m = d$. The detail parameters are listed in Table 3-6.

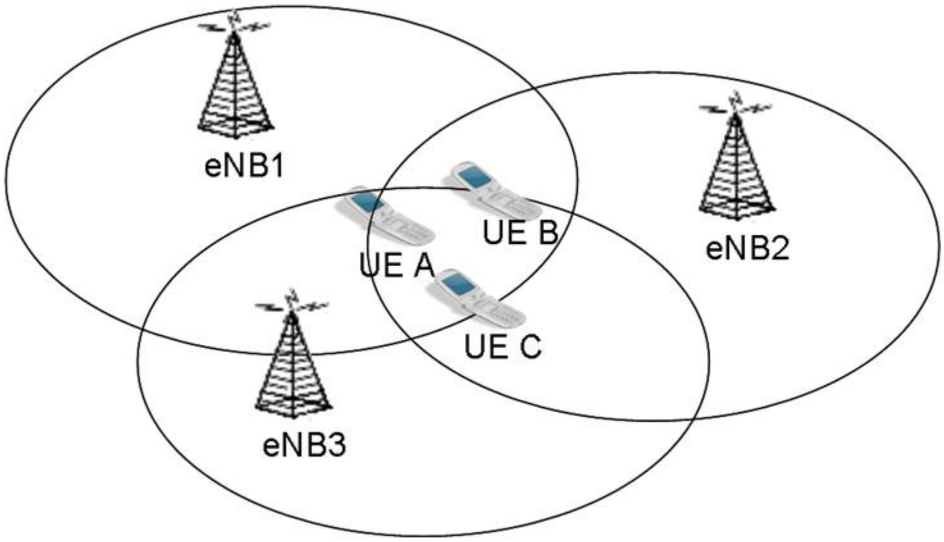


**Figure 3-2**: Simulation configuration of the CoMP systems

**Table 3-6**: Simulation parameters

| **Parameter** | **Value** |
|---|---|
| Channel | Rayleigh fading channel |
| Number of BSs | 3 |
| Number of UEs | 3 |
| Number of transmit antennas | 2, 4 |
| Number of receive antennas | 2, 4 |
| Number of transmitted signal layers | 1, 2, 3, 4 |
| Number of Max-SINR IA iterations | 1000 |
| Backhaul link | Perfect information exchange between BSs |
| Codebook | LTE UL codebook [15] |

Firstly, we show the sum-rate performance of exact IA and codebook-based IA in the UL CoMP system with different antenna configurations. Exact IA means that the central processor feeds back the complete precoder matrix to the cooperated UEs. In codebook-based IA, the central processor only feeds back the precoder index to the cooperated UEs. Figure 3-3 and Figure 3-4 show the sum-rate performance with $d$ = 1, $N_t$ = 4, $N_r$ = 2 and $N_r$ = 4, respectively. The results show that the performance gap between exact IA + CoMP and conventional CoMP is larger in Figure 3-3 than in Figure 3-4. This is because IA can improve the CoMP capacity performance especially in severe interference environments. Figure 3-3 and Figure 3-4 also include the results of codebook-based IA using the LTE UL 1-layer codebook in Table 3-2. The proposed codebook-based IA effectively reduces the feedback information with only a slight sum-rate performance degradation.

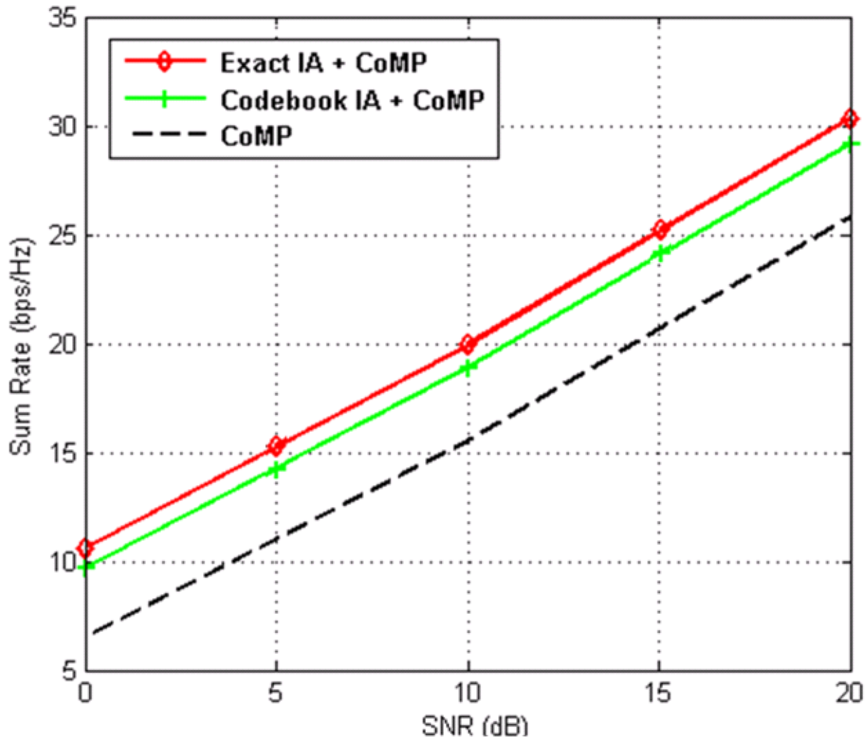


**Figure 3-3**: Sum-rate performance of exact IA, codebook-based IA, and conventional CoMP with $d$ = 1, $N_t$ = 4, $N_r$ = 2, no. of iterations = 1000

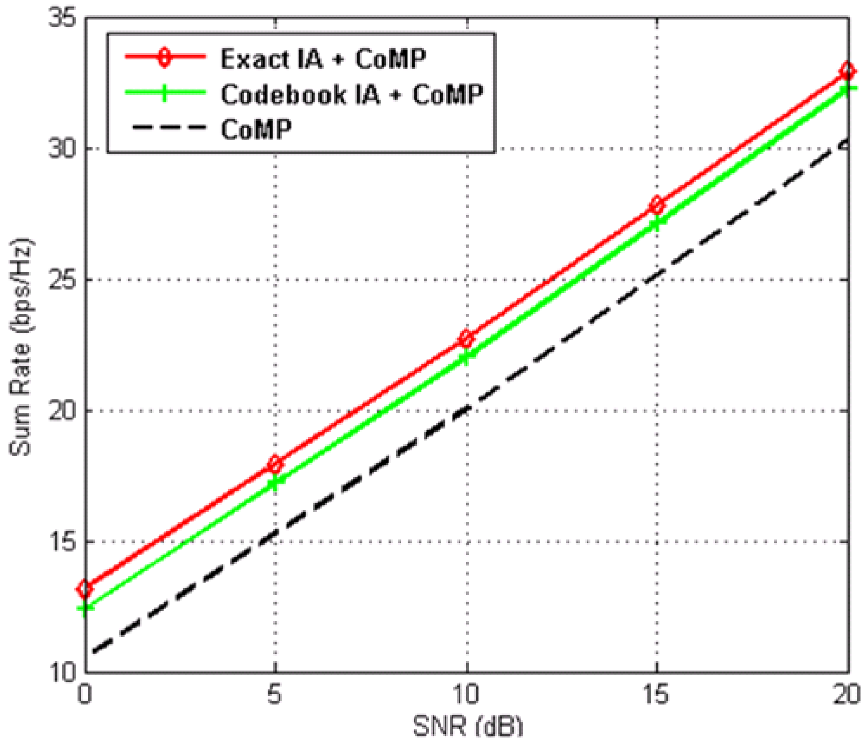


**Figure 3-4**: Sum-rate performance of exact IA, codebook-based IA, and conventional CoMP with $d = 1$, $N_t = 4$, $N_r = 4$, no. of iterations = 1000

Then, we show the performance of exact IA and codebook-based IA with the same antenna configuration but with different numbers of transmitted signal layers. Figure 3-5 shows the sum-rate performance of exact IA and codebook-based IA with $N_t = 4$, $N_r = 4$ and different numbers of signal layers *d*. With more transmitted signal layers, the overall interference becomes more severe. This is confirmed by the simulation results in which the performance gap between exact IA + CoMP and conventional CoMP is largest with $d = 3$. The results also confirm the effectiveness of codebook-based IA with exhaustive precoder search which adopts the LTE UL codebook with $d = 1, 2, 3$ as Table 3-2 to Table 3-4, respectively.

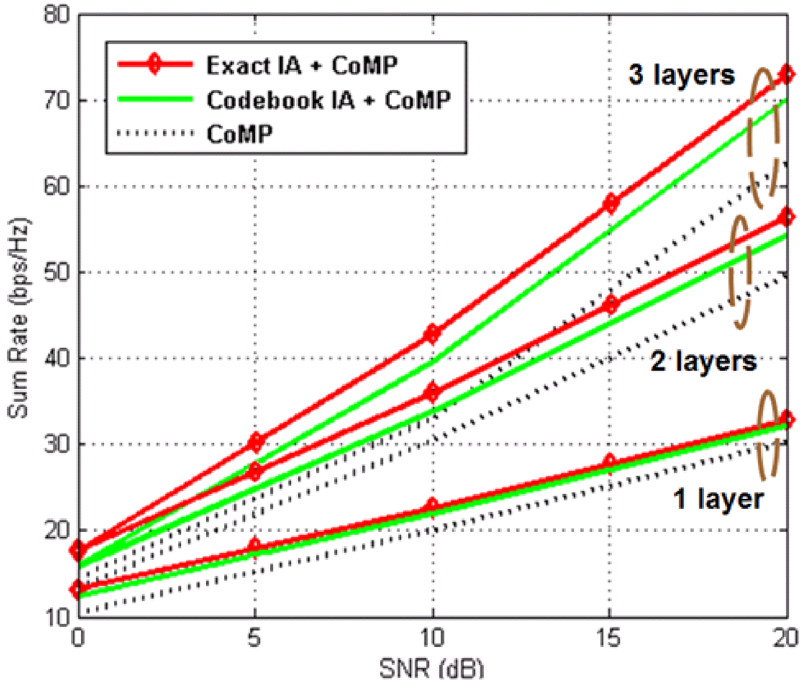


**Figure 3-5**: Sum-rate performance of exact IA, codebook-based IA, and conventional CoMP with $d = 1, 2, 3$, $N_t = 4$, $N_r = 4$, no. of iterations = 1000

## 3.5 Summary

In this chapter, we first reformulate various popular IA algorithms in UL CoMP systems such as Min-leakage IA and Max-SINR IA algorithms. Since the Min-leakage IA makes no attempt to maximize the desired signal power within the desired signal subspace, the alternative Max-SINR IA algorithm which considers the signal power is adopted in this thesis. To implement the IA algorithm in centralized UL CoMP systems, the codebook-based IA in UL CoMP systems is proposed with less feedback information. As shown in computer simulations, the IA technique ensures the performance improvement in UL CoMP systems with different antennas and different no. of transmitted signal layers. The simulations have also shown that the proposed codebook-based IA effectively reduces the feedback information with only a slight sum-rate degradation.

# Chapter 4

# Efficient Precoder Search Method and Proposed Codebook Design

In this chapter, we introduce an efficient precoder search method and several effective codebook design methods in the codebook-based IA. In the codebook-based IA, we need to perform an exhaustive precoder search to obtain the desired optimal solutions. However, the exhaustive search is inefficient in the central processor especially when the codebook size or the number of serving UEs is large. In Section 4.1, we introduce an efficient *K*-Best precoder search method in the codebook-based IA. The concept of *K*-Best search is originally introduced in the sphere decoding algorithm for MIMO detection. We next introduce several codebook extension methods to improve the performance of the codebook-based IA in UL CoMP systems in Section 4.2. Computer simulations are shown in Section 4.3. A summary of Chapter 4 is given in Section 4.4.

## 4.1 Proposed *K*-Best Precoder Search Method

In the codebook-based IA, we need to perform an exhaustive precoder search to obtain the desired solution. The exhaustive search is inefficient in the central processor especially when the codebook size or the number of serving UEs is large. Therefore, to reduce the computational load in the optimal precoder search, we adopt the *K*-Best precoder search algorithm to efficiently perform the precoder selection. The concept of the *K*-Best search was originally introduced in the SDA for MIMO detection [16]. The *K*-Best SDA uses breadth-first search and keeps *K* best candidates at each layer for the next layer search, thereby maintaining a lower complexity than the conventional SDA.

The main idea of the *K*-Best precoder search method is to keep only *K* promising precoder candidates at each UE level having the maximum SINR. The $K$-Best method disregards the dropped precoders and equivalently excludes the unnecessary computations for corresponding joint decoder and equalizer as depicted in Figure 4-1. An effective Max-SINR precoder selection criterion $\forall m \in \{1,2,\ldots,M\}$, $\forall i \in \{1,2,\ldots,d_m\}$ based on the codebook-based IA system model of Section 3.3 in the central processor can be formulated as

$$\max_{\bar{\mathbf{V}}} \left\| \frac{\bar{\mathbf{U}}^{((m-1)d_m+i)H}\mathbf{H}_m\bar{\mathbf{V}}^{((m-1)d_m+i)}\bar{\mathbf{V}}^{((m-1)d_m+i)H}\mathbf{H}_m^H\bar{\mathbf{U}}^{((m-1)d_m+i)}}{\bar{\mathbf{U}}^{((m-1)d_m+i)H}\bar{\mathbf{B}}_m^{(i)}\bar{\mathbf{U}}^{((m-1)d_m+i)}} \right\|. \quad (4.1)$$

where $\bar{\mathbf{U}}$ is the joint decoder matrix computed by the central processor, $\bar{\mathbf{V}}$ is the diagonal precoder matrix composed by the existing precoder, and $\bar{\mathbf{B}}$ is the interference plus noise matrix. The steps of codebook-based IA with the efficient *K*-Best selection method in CoMP systems are summarized as follows:

Step 1.

Start with arbitrary precoders $\bar{\mathbf{V}}_m$ at each UE choosen from the existing codebook.

Step 2.

Central processor adopts all precoders from the existing codebook at the $m$th UE level to compute the joint decoder $\mathbf{U}$. The precoders adopted in other UE levels are the same as step 1.

Step 3.

Central processor keeps only $K$ precoder candidates at the $m$th UE level based on the value of Equation (4.1).

Step 4.

Iteratively process Step 2 and Step 3 at the $(m+1)$th UE level and keep $K$ precoder candidates at the last UE level.

Step 5.

Central processor collects $K$ precoder candidates and the corresponding joint decoder to compute the corresponding sum-rate. After sum-rate computation, the central processor feeds back the max-rate precoder matrix index to each UE from $K$ candidates.

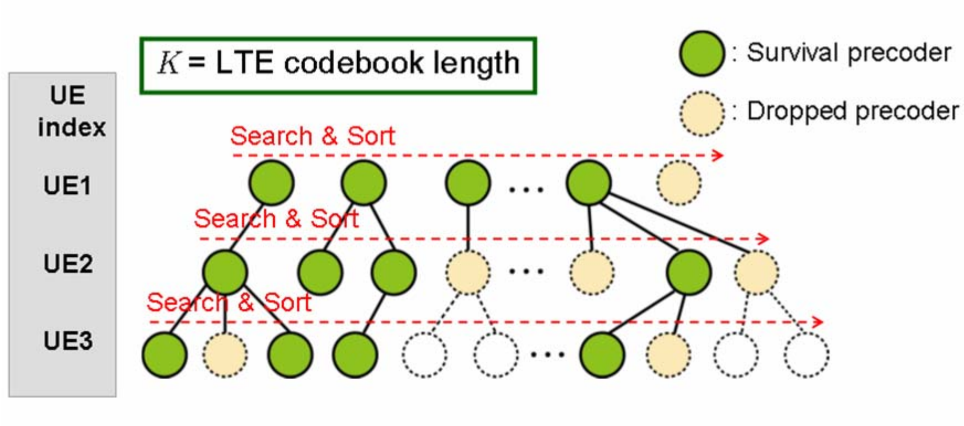


**Figure 4-1**: Illustration of $K$-Best precoder selection

The computational complexity of the exhaustive precoder search grows exponentially with the number of UEs and the codebook size. The computational complexity of Equation (4.1) and the sorting procedure with exhaustive search can be formulated as

$$\frac{K(K^M-1)}{K-1}+K^M\log(K^M). \tag{4.2}$$

where $K$ is equal to the codebook size and $M$ is the number of UEs. The first term of Equation (4.2) is the summation of computational complexity of Equation (4.1) at all UE levels. The second term is the computational complexity of the quick sorting algorithm at the last UE level. However, as shown in Figure 4-2, the computational complexity of the $K$-Best search is proportional to a polynomial function of the number of UEs and K. The computational complexity of Equation (4.1) and the sorting procedure with $K$-Best search can be formulated as

$$\left[K+(M-1)K^2\right]+\left[K\log(K)+(M-1)K^2\log(K^2)\right]. \tag{4.3}$$

The first term of Equation (4.3) is the summation of computational complexity of Equation (4.1) at all UE levels. The second term is the summation of computational complexity of the quick sorting algorithm at all UE levels. Hence, the computational load saving by the $K$-Best method is significant especially when adopting a large size codebook or serving a large number of UEs in the UL CoMP system.

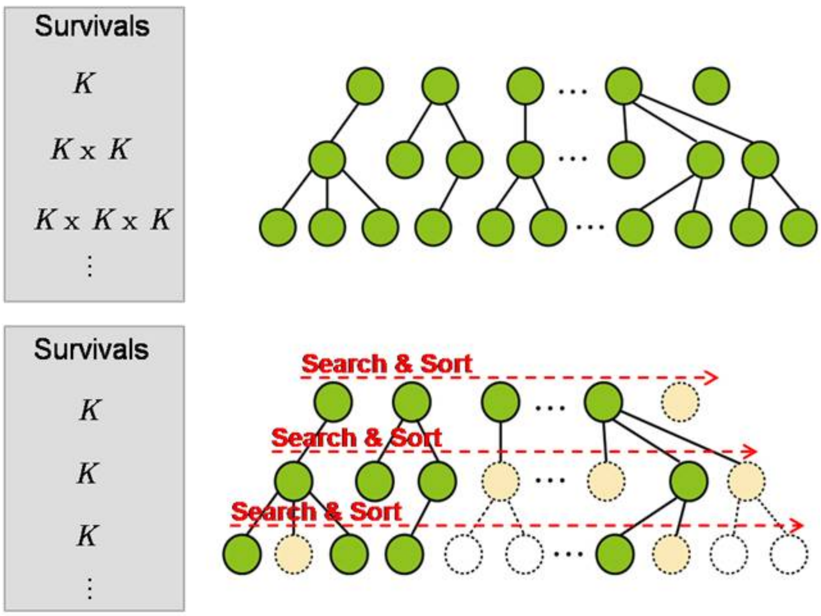


**Figure 4-2**: Complexity comparison of exhaustive search and *K*-Best search

## 4.2 Proposed Codebook Design

After solving the computational load problem, we want to further improve the performance of codebook-based IA with several codebook extension methods. In codebook-based IA, the performance is bounded by the fixed beam patterns of the selected precoders in the existing codebook. Therefore, the objective of the extension methods is aimed to approach the exact IA precoder by extending the existing precoder beam patterns. A case of 2-layer precoder beam pattern is shown in Figure 4-3 (The beam patterns of the first layer and the second layer in the precoder are shown as left part and right part in Figure 4-3). As shown in Figure 4-3, the beam patterns of the 2-layer precoder from the extended codebook are closer to the exact IA than that of the precoder from the original codebook. In order to approach the exact IA precoder, the utilized extension methods can be classified into scale extension and phase rotation extension method [18]. However, the scale factors in the scale extension method are difficult to determine. Hence, we focus on the phase rotation extension method and propose a layer-wise phase rotation method to further improve the performance of codebook-based IA.

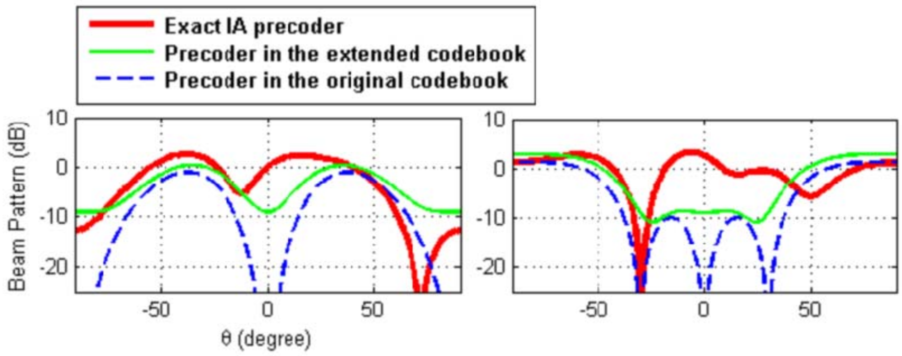


**Figure 4-3**: Illustration of 2-layer precoder beam pattern with exact IA precoder, precoder in the extended codebook, and precoder in the original codebook

The scale extension method is aimed to alter the beam pattern of the precoder in the existing codebook as shown in Figure 4-4. The main objective of the scale extension method is to enhance specific precoder entries by scale factors. The scale method can be formulated as follows:

$$\bar{\mathbf{V}}_{\text{scale}} = \mathbf{S}\bar{\mathbf{V}}, \tag{4.4}$$

$$\mathbf{S} = \text{diag}\{[\alpha_1,\ldots,\beta,\ldots,\alpha_{N_t-1}]\}, \tag{4.5}$$

where $\bar{\mathbf{V}}$ is the precoder from original LTE UL codebook, $\mathbf{S}$ is the scale matrix composed by the scale factor $0<\alpha<1$ and the corresponding factor $\beta$, and $\bar{\mathbf{V}}_{\text{scale}}$ is the scaled extension precoder. However, the scale method is cannot systematically decide the value of scale factor $\alpha$. Hence, we focus on the phase rotation extension method in this work.

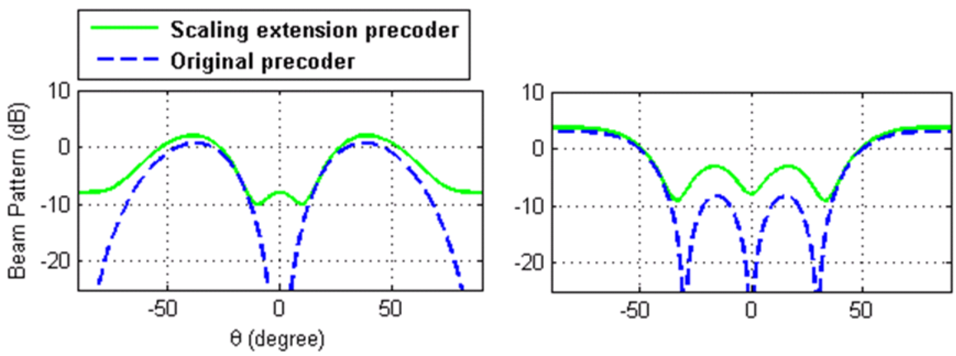


**Figure 4-4**: Illustration of 2-layerd precoder beam pattern with scale extension

The phase extension method is aimed to rotate the whole beam pattern of the precoder in the existing codebook as shown in Figure 4-5. The phase extension method can be formulated as follows [17]:

$$\bar{\mathbf{V}}_{\text{rot}} = \mathbf{P}_1(\theta_1)\bar{\mathbf{V}}, \tag{4.6}$$

$$\mathbf{P}_1(\theta_1) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{j\theta_1} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & e^{j(N_t-1)\theta_1} \end{bmatrix}, \tag{4.7}$$

where $\bar{\mathbf{V}}$ is the precoder from original codebook, $\mathbf{P}_1$ is an unitary rotation matrix, $\{-\pi/2 < \theta_1 < \pi/2\}$ is the angle of the phase rotation, and $\bar{\mathbf{V}}_{\text{rot}}$ is the extended codebook. The value of $\theta_1$ can be uniformly quantized by several extra extension bits. The phase rotation is a simple extension method which effectively creates more precoder options in the codebook-based IA. However, since the phase extension method rotates the entire precoder matrix, the slight angle rotation of the whole precoder matrix makes no effort to further approach the IA precoder when adopting a large number of extension bits.

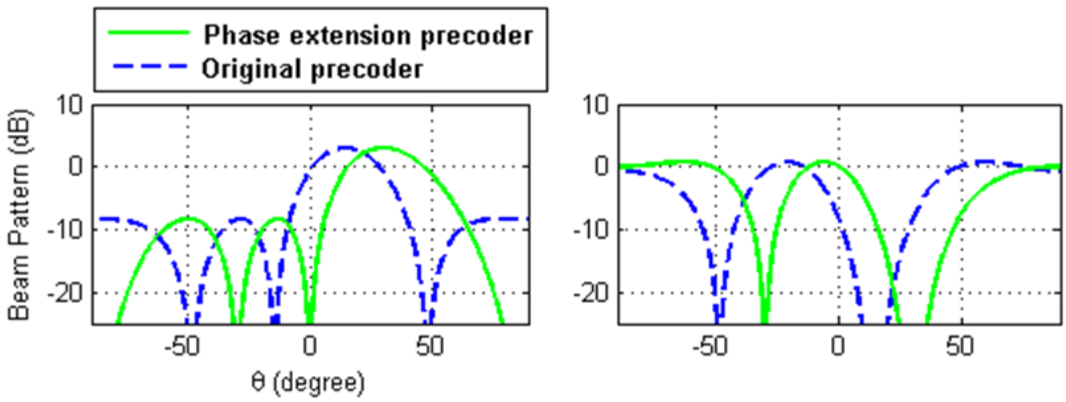


**Figure 4-5**: Illustration of 2-layer precoder beam pattern with phase extension

In order to further improve the performance of phase extension, we here propose a layer-wise phase extension method. A 2-layer precoder beam patterns of the layer-wise phase rotation method are shown in Figure 4-6. In layer-wise phase rotation method, the rotation is individually performed at each layer in the precoder matrix. The layer-wise phase rotation method can be formulated as follows:

$$\bar{\mathbf{V}}_{\mathrm{rot2}}^{(d_m)} = \mathbf{P}_2(\theta_2)\bar{\mathbf{V}}^{(d_m)}, \tag{4.8}$$

$$\mathbf{P}_2(\theta_2) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{j\theta_2} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & e^{j(N_t-1)\theta_2} \end{bmatrix}, \tag{4.9}$$

where $\bar{\mathbf{V}}$ is the precoder from the original codebook, $d_m$ is the no. of transmitted signal layers in the precoder, $\bar{\mathbf{V}}^{(d_m)}$ is the $d_m$th column of the precoder, $\mathbf{P}_2$ is the unitary rotation matrix, $\{-\pi / 2 < \theta_2 < \pi / 2\}$ is the angle of the phase rotation which can be quantized by extra extension bits, and $\bar{\mathbf{V}}_{\mathrm{rot2}}^{(d_m)}$ is the $d_m$th column of extended precoder composed by the layer-wise phase rotation method.

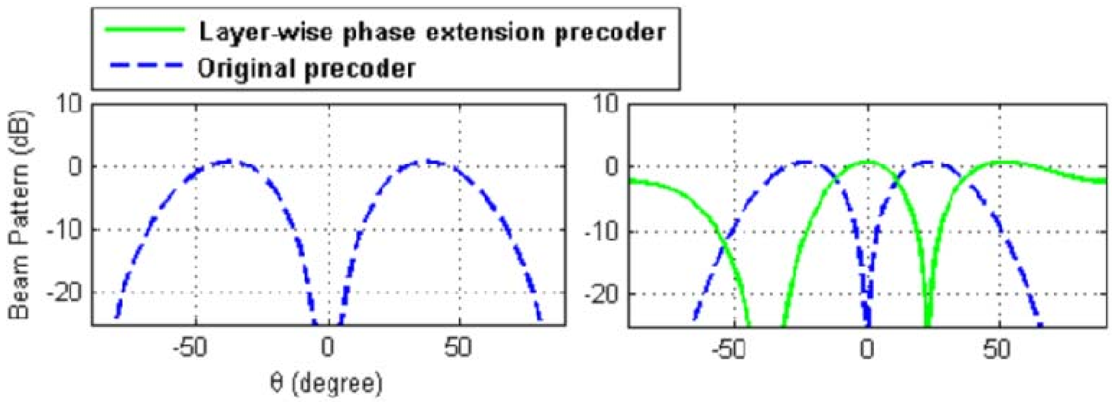


**Figure 4-6**: Illustration of 2-layer precoder beam pattern with layer-wise phase extension

# 4.3 Computer Simulations

In this section, we first simulate the sum-rate performance of Max-SINR IA and codebook-based IA with exhaustive search and $K$-Best precoder search. Then, we simulate the sum-rate performance of Max-SINR IA, codebook-based IA with the original LTE UL codebook, codebook-based IA with the phase extended codebook, and the codebook-based IA with the proposed layer-wise phase extended codebook. For the simulation configuration, we consider three BSs in the cooperation group and one UE in coverage of each BS ($M$ = 3, $P$ = 1). The channel matrices are assumed i.i.d. complex Gaussian with unit variance. Each BS is equipped with $N_r$ antennas and each UE is equipped with $N_t$ antennas. We also assume that all UEs transmit with same number of signal layers i.e. $d_m = d$. The detail parameters are listed in Table 4-1.

**Table 4-1**: Simulation parameters

| **Parameter** | **Value** |
|---|---|
| Channel | Rayleigh fading channel |
| Number of BSs | 3 |
| Number of UEs | 3 |
| Number of transmit antennas | 4 |
| Number of receive antennas | 4 |
| Number of transmitted signal layers | 2, 3, 4 |
| Number of Max-SINR IA iterations | 1000 |
| Backhaul link | Perfect information exchange between BSs |
| Original codebook | LTE UL codebook [15] |

Firstly, we show the sum-rate performance of exact IA and codebook-based IA with exhaustive precoder search and $K$-Best precoder search with $N_t = 4$, $N_r = 2$, and $d = 1$ as shown in Figure 4-7. Here we adopt the LTE UL 1-layer codebook, and the $K$ is equal to the 1-layer codebook size (i.e., $K = 24$). The result shows that the $K$-Best search maintains the same sum-rate performance as exhaustive search. We repeat the simulations with $N_t = 4$, $N_r = 4$, and $d = 3$ and show the results in Figure 4-8. Here $K$ is equal to the 3-layer codebook size (i.e., $K = 12$). It is seen that the $K$-Best method still maintains a good performance even with a small value of $K$. Moreover, we list the percentage of complexity reduction of $K$-Best search relative to exhaustive search with different number of transmitted signal layers in Table 4-2.

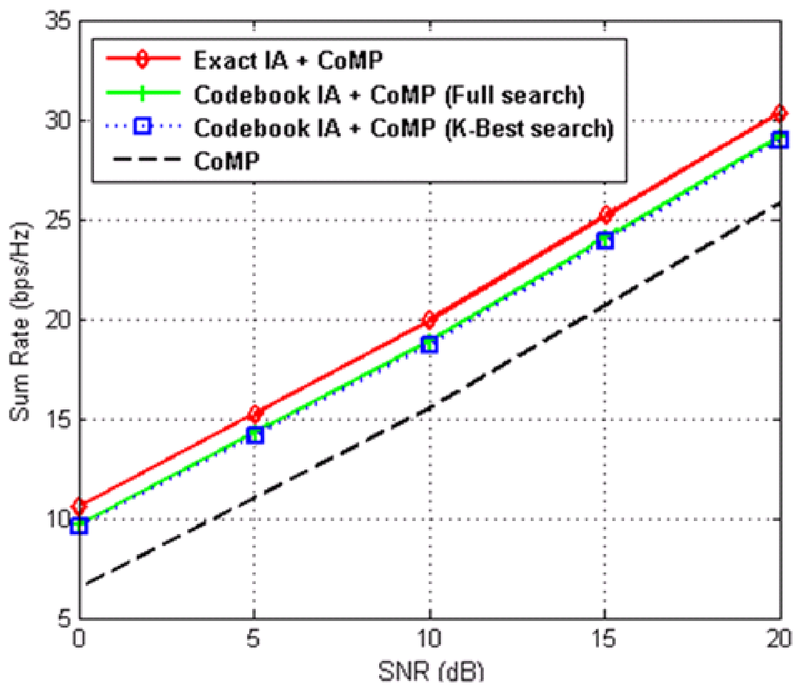


**Figure 4-7**: Sum-rate performance of exact IA, codebook-based IA (Full search), codebook-based IA ($K$-Best search) and conventional CoMP with $d = 1$, $N_t = 4$, $N_r = 2$, no. of iterations = 1000, $K = 24$

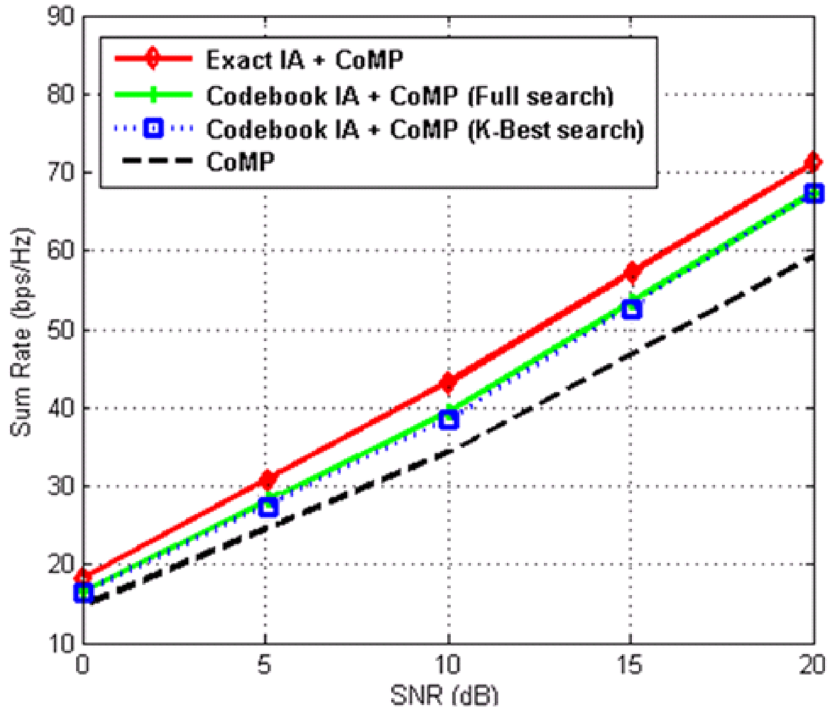


**Figure 4-8**: Sum-rate performance of exact IA, codebook-based IA (Full search), codebook-based IA (*K*-Best search) and conventional CoMP with $d = 3$, $N_t = 4$, $N_r = 4$, no. of iterations = 1000, $K = 12$

**Table 4-2**: The percentage of complexity reduction of *K*-Best search relative to exhaustive search with $d = 1, 2, 3$, $N_t = 4$, $N_r = 4$

| No. of signal layers | 1 | 2 | 3 |
|---|---|---|---|
| Codebook size ($K$) | 24 | 16 | 12 |
| Percentage of complexity reduction | 94% | 92% | 88% |

Then, we show the sum-rate performance of exact IA, codebook-based IA with phase extended codebook, and codebook-based IA with original UL codebook. Figure 4-9 shows the sum-rate performance with $d = 2$, $N_t = 4$, $N_r = 4$, and the number of extra extension bits is 4 or 2. The results show that the performances of codebook-based IA with extended codebooks (4-bits extension and 2-bits extension) are better than the codebook-based IA with original LTE UL codebook. This is because that the codebook-based IA algorithm can find a more suitable solution from the extended codebook. The simulation result also shows that the performance of codebook-based IA with 4-bit phase extension method is better than the 2-bit case. This is because that the precoder solutions from the 4-bits extended codebook are closer to the exact IA solutions than that from the 2-bits case.

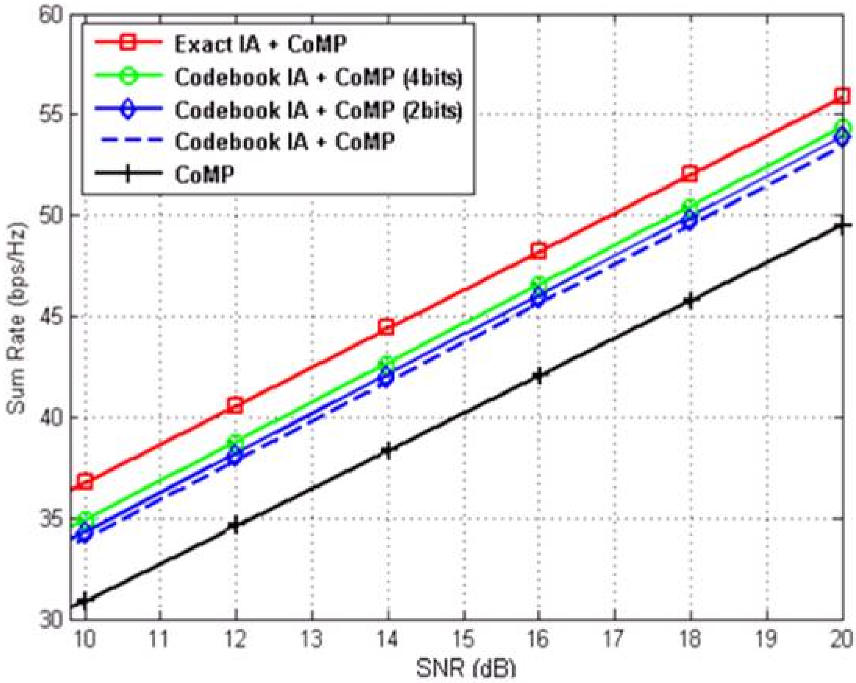


**Figure 4-9**: Sum-rate performance of exact IA, codebook-based IA with different codebook (4-bits extension, 2-bits extension, and original codebook), and conventional CoMP with $d = 2$, $N_t = 4$, $N_r = 4$, no. of iterations = 1000

However, the performance of the phase extension is bounded when the number of extension bits is large. Figure 4-10 shows the percentage gain of codebook-based IA compared to the conventional CoMP with SNR = 20, $d$ = 2, $N_t$ = 4, $N_r$ = 4, and the number of extra extension bits is 0 to 7. The result shows that the performance of the codebook-based IA with phase extension is saturated when the number of extension bits is large. This is due to that the slight angle phase rotation of the whole precoder matrix makes no effort to further approach the exact IA precoder. Thus, cooperation between proposed layer-wise phase extension and the phase extension of the whole precoder matrix is needed.

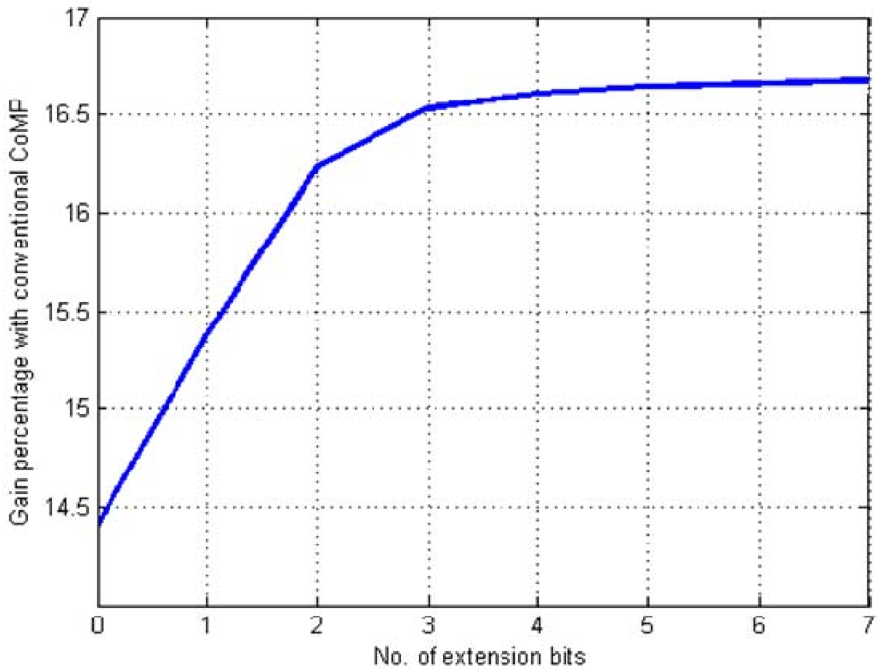


**Figure 4-10**: Illustration of performance saturation of phase extension method with SNR = 20, $d$ = 2, $N_t$ = 4, $N_r$ = 4, no. of iterations = 1000

In order to demonstrate the performance improvement due to the proposed layer-wise extension, we show the sum-rate performance of codebook-based IA with different extension methods. Figure 4-11 shows the sum-rate performance with $d$ = 3, $N_t$ = 4, $N_r$ = 4, and the number of extra extension bits is 6. In the phase extension simulations, the rotation angle of the whole precoder is quantized with 6 bits. In the mixed extension simulation, the rotation angle of the whole precoder and each layer of the precoder are quantized with a total of 6 bits. The result shows that the performance of the mixed extension method is better than the phase extension method. This is because that the layer-wise phase rotation method can effectively overcome the performance saturation of the phase rotation method.

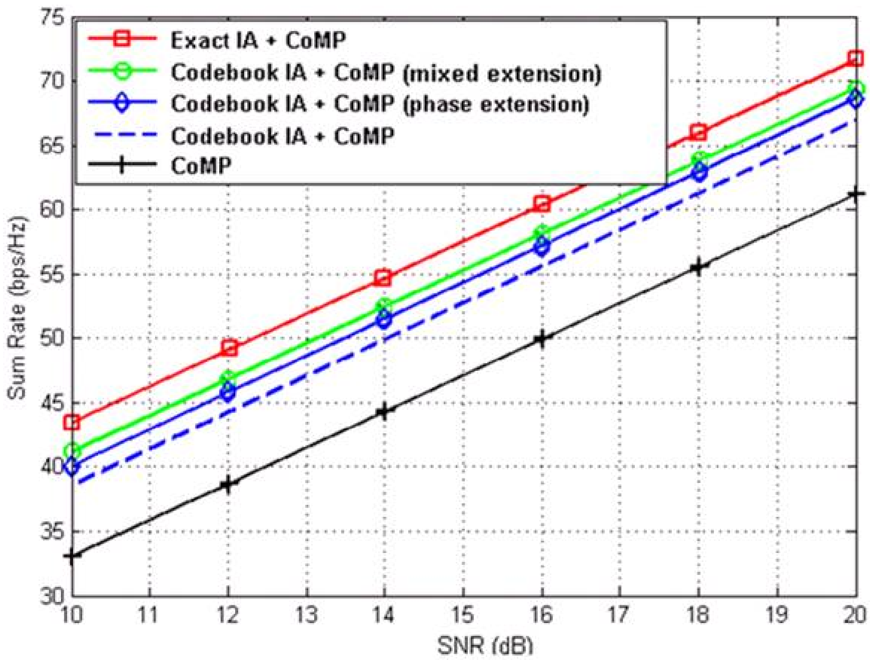


**Figure 4-11**: Sum-rate performance of exact IA, codebook-based IA with different codebook (mixed extension, phase extension, and original codebook), and conventional CoMP with $d$ = 3, $N_t$ = 4, $N_r$ = 4, no. of iterations = 1000

## 4.4 Summary

In this chapter, we first introduce an efficient and effective *K*-Best precoder search method which avoids the computational burden of exhaustive precoder search in the codebook-based IA. The simulations show that the *K*-Best precoder search still maintains the same sum-rate performance as exhaustive search. After solving the heavy computational load problem, we introduce several codebook extension methods to improve the performance of codebook-based IA. To tackle the performance saturation of the phase extension method, we propose an effective layer-wise phase extension method to further improve the sum-rate performance of codebook-based IA.

# Chapter 5

# Conclusions and Future Works

Adopting IA in centralized UL CoMP with full cooperation at the receiver has been shown to effectively improve the sum-rate performance. In the UL CoMP system with Max-SINR IA technique, the central processor collects channel information and all the received signals to compute the corresponding precoder and joint decoder which satisfy the Max-SINR IA design criterion. Considering the feasibility of implementing IA in UL CoMP systems, the codebook-based IA is proposed which effectively reduces the amount of feedback information. To avoid the exponentially growing computational burden of exhaustive precoder search in codebook-based IA, an efficient *K*-Best precoder search method is further proposed. After solving the computational load problem, we next introduce several codebook extension methods to improve the performance of the codebook-based IA.

In Chapter 2, we first give a review of UL centralized CoMP systems. In centralized CoMP, the received signal and the channel information from all BSs are collected by the central processor which decodes the signal jointly. We also introduce the IA concept and the corresponding IA precoder and decoder design criterion in *K*-user systems. In view of the interference resistant ability of IA technique, we adopt the centralized IA technique and reformulate the IA design criterion in UL CoMP systems.

In Chapter 3, we first reformulate various popular IA algorithms in UL CoMP systems such as Min-leakage IA and Max-SINR IA algorithm. Since the Min-leakage IA makes no attempt to maximize the desired signal power within the desired signal subspace, we adopt the alternative Max-SINR IA algorithm which considers the desired signal power. To implement the IA algorithm in centralized UL CoMP systems, the central processor needs to feed back the corresponding precoder matrix to each UE. However, in practice, the feedback information is limited by the capacity of the control channels. Hence, the codebook-based IA in UL CoMP systems is proposed with less feedback information. Simulations demonstrate that the proposed codebook-based IA effectively reduces the feedback information with only a slight sum-rate performance degradation.

To avoid the exponentially growing computational burden of exhaustive precoder search in codebook-based IA, an efficient and effective $K$-Best precoder search method is proposed. The computational load saving achieved by the $K$-Best method is significant especially when adopting a large size codebook or serving a large number of UEs in UL CoMP systems. Simulations demonstrate that the $K$-Best search maintains the same sum-rate performance as exhaustive search. After solving the heavy computational load problem, we introduce several codebook extension methods to improve the performance of codebook-based IA. Moreover, to tackle the performance saturation of the phase extension method, we propose an effective layer-wise phase extension method.

The main contributions of this thesis are as follows. First, we propose the codebook-based IA technique which effectively reduces the amount of feedback information with only a slight sum-rate performance degradation. Moreover, the proposed $K$-Best efficient precoder search method effectively saves the computational load especially when adopting a large size codebook or serving a large number of UEs in UL CoMP systems. Finally, the proposed layer-wise phase extension method effectively overcomes the performance saturation of the existing phase extension method.

There are some future works worthy of further investigation. The first one is that the channel is assumed to be uncorrelated and perfectly estimated in this thesis. However, the effects of correlated channel and channel estimation errors need to be considered. The second one is that the information through the backhaul connection between the cooperating BSs is assumed to be perfectly exchanged. In practice, information exchange delay or information exchange losses between the BSs need to be considered. At last, the max-rate selection criterion can be considered in the $K$-Best precoder selection method.

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