Front. Electr. Electron. Eng. China 2011, 6(4): 515–520
DOI 10.1007/s11460-011-0110-x

RESEARCH ARTICLE

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Power allocation for collaborative transmission in LTE-Advanced

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Abstract Collaborative transmission among evolved Node-Bs (eNBs) is one of the promising techniques for LTE-Advanced to provide broader coverage and higher spectral efficiency. The interference among multi-cell transmission can be mitigated by joint precoding, such as multi-cell block diagonalization (BD) at cooperative eNBs. The major difference between multi-cell and single-cell transmission is that the power constraint has to be considered on a per-eNB basis. To satisfy per-eNB power constraint (PePC), a simplified power allocation algorithm for the multi-cell BD based collaborative transmission is proposed in this paper. The algorithm provides a power allocation coefficient matrix for BD to meet PePC. Simulation results demonstrate that the proposed algorithm has a near-optimal performance with simplicity.

Keywords LTE-Advanced, coordinated transmission, per-eNB power constraint (PePC), block diagonalization (BD)

1 Introduction

In cellular system, users at the cell boundary are known to experience a large inter-cell interference (ICI) with a frequency reuse factor equal to 1, for the transmission in each cell acts as interference to other cells [1,2]. To mitigate ICI, coordinated transmission among multiple geographically separated cells was proposed to improve the coverage and network spectral efficiency for LTE-Advanced system in 2008 [3]. By sharing information, such as data, scheduling, and channel state information (CSI) across multiple evolved Node-Bs (eNBs) and configuring joint processing at cooperative eNBs, the ICI will be minimized or even cancelled.

For the downlink, complete multi-user interference pre-cancellation can be performed if the CSI of all users is known at eNB. The dirty paper coding (DPC) [4], which has been proven to be the capacity optimal technique, uses successive interference cancellation approach by introducing complex encoding and decoding. It is an information theoretic concept that is difficult to implement in practice. For this reason, linear processing is more attractive to the real system. Zero-forcing (ZF) beamforming [5,6] for single-antenna user employs complete diagonalization using pseudo-inversion of the channel to cancel the multi-user interference. However, the user with multiple receive antennas can coordinate its own receiver outputs, which makes ZF to be suboptimal in that case. In this paper, we utilize block diagonalization (BD) algorithm [7–10] for multi-antenna users. BD algorithm uses singular value decomposition (SVD) to calculate the null space of channel transmission matrix. Therefore, this scheme can eliminate the interference among different receivers other than the intra-receiver interference.

Most of the previous studies on multi-cell coordination apply BD precoding algorithm with total power constraint (TPC) [7–9] to eliminate ICI. However, in coordination systems, each eNB transmits multiple users' data with different precoding weights in a resource block (RB) simultaneously, which may cause the transmit power per eNB to exceed the limit when TPC is adopted. Per-base transceiver station (Per-BTS) power constraints were introduced for networked multiple-input multiple-output (MIMO) in Ref. [10], but the scaling factor that could ensure the precoding matrix to meet the power constraint is still difficult to derive.

Our objective in this paper is to investigate per-eNB power constraint (PePC) for the downlink of eNB coordinated LTE-Advanced system and propose simplified

Received January 28, 2010; accepted March 28, 2011

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power allocation algorithm combined with BD precoding matrix to satisfy PePC. We have made some idealized assumptions in this paper, such as perfect information about channel state. We demonstrate through system level simulation that the proposed power allocation algorithm has a near-optimal performance with simplicity.

The rest of this paper is organized as follows: Section 2 illustrates necessary assumptions and describes the system model of coordinated transmission. The precoding matrix designed for multi-cell BD is presented in Sect. 3. The proposed power allocation approach is stated in Sect. 4. Simulation results are given in Sect. 5, and Sect. 6 presents some concluding remarks.

2 System model

We assume that the downlink of MIMO system has n_{T} transmit antennas at each eNB and m_{R} receive antennas at each user equipment (UE). The network is divided into several coordination clusters, where each cluster contains N adjacent cells. Within a cluster, the cooperative eNBs perform joint processing using the shared information, such as scheduling, CSI and data. Therefore, the ICI will be suppressed, and the spectral efficiency will be improved.

Assumption 1 *The channel estimation is ideal.*

This assumption is to ensure the ICI cancellation capability. The effect of channel estimation error on BD precoding algorithm is not discussed here, and we assume that the sounding reference signals, reference signals targeting CSI estimation, and data channel demodulation are estimated with no error.

Assumption 2 *eNBs can fully share the perfect CSI and data of all users in the same cluster.*

The CSI and data of all users in a cluster is used for multi-cell multi-user precoding to eliminate ICI. Due to channel reciprocity in the time-division duplexing (TDD) system, the downlink CSI can be obtained by estimating uplink reference channel. However, in the frequency-division duplexing (FDD) system, the downlink CSI at the transmitter can be obtained only by feedback from users, which is not explored in this paper.

From the above assumptions, the downlink of cellular MIMO system is extended to an $(Nn_{\mathrm{T}}) \times (Mm_{\mathrm{R}})$ virtual MIMO architecture by joint precoding and transmission, as shown in Fig. 1, where M is the number of users allocated on the same time-frequency RB within a cluster, and these M users are known as UE-pair at eNB side.

Assumption 3 *The user pairing information is transparent to UE.*

Due to their geographical dispersion, coordination among users is difficult; thus, we assume that UE does not know the paired users' information, and the UE side reception is assumed to be independent.

Let $\boldsymbol{H}_k \in \mathcal{C}^{m_{\mathrm{R}} \times Nn_{\mathrm{T}}}$ $(1 \leqslant k \leqslant M)$ denote the downlink channel matrix of the kth user, which consists of both small-scale fading and large-scale fading. The small-scale fading can be modeled as independent and identically distributed complex Gaussian random variables with variance of 0.5 per dimension, while the large-scale fading is composed of pathloss and shadowing fading. Take vector $\boldsymbol{S}_k \in \mathcal{C}^{r_k \times 1}$ to present the data intended for the kth UE, where r_k depends on the number of independent data streams transmitted to user k. $\boldsymbol{S}_k$ is preprocessed at the transmitter with $(Nn_{\mathrm{T}}) \times r_k$ beamforming matrix $\boldsymbol{W}_k$, which is obtained by using multi-cell BD algorithm at transmitter. The transmitted signal vector of user k after precoding can be denoted as $\boldsymbol{W}_k\boldsymbol{S}_k$.

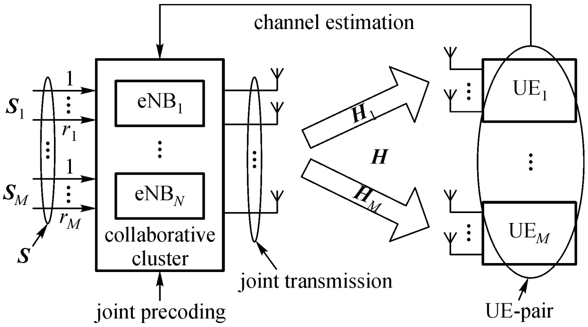

Fig. 1 Downlink of coordinated transmission

3 Multi-cell block diagonalization

In coordinated cellular system with joint precoding, the received signal vector of the kth user can be expressed as

$$\boldsymbol{R}_k = \underbrace{\boldsymbol{H}_k\boldsymbol{W}_k\boldsymbol{S}_k}_{\text{desired signals}} + \underbrace{\boldsymbol{H}_k \sum_{j=1, j\neq k}^{M} \boldsymbol{W}_j\boldsymbol{S}_j}_{\text{interference within the cluster}} + \underbrace{\sum_i \sum_{j=1}^{M} \boldsymbol{H}_k^{(i)} \boldsymbol{W}_j^{(i)} \boldsymbol{S}_j^{(i)}}_{\text{interference from other clusters}} + \underbrace{\boldsymbol{n}_k}_{\text{noise}}, \tag{1}$$

where the superscript (i) indicates the interference from the ith neighboring cluster. Each element of $\boldsymbol{n}_k$ designates the receiver thermal noise modeled as additive white Gaussian noise (AWGN) vector with zero mean and variance σ_n^2.

To precancel the interference within the coordination cluster, which is usually strong, the precoding matrix $\boldsymbol{W}_k$ should fulfill the constraint [7]

$$\boldsymbol{H}_k \sum_{j=1, j\neq k}^{M} \boldsymbol{W}_j = 0, \tag{2}$$

which means all multi-user interference within this cluster will be eliminated.

Due to Assumption 1 and 2, $\overline{\boldsymbol{H}}_k$ is defined as the channel matrix for all users other than user k combined:

$$\overline{\boldsymbol{H}}_k = [(\boldsymbol{H}_1)^{\mathrm{T}} \ \cdots \ (\boldsymbol{H}_{k-1})^{\mathrm{T}} \ (\boldsymbol{H}_{k+1})^{\mathrm{T}} \ \cdots \ (\boldsymbol{H}_M)^{\mathrm{T}}]^{\mathrm{T}}, \quad (3)$$

where superscript T indicates the transpose.

The zero multi-user interference constraint forces $\boldsymbol{W}_k$ to lie in the null space of $\overline{\boldsymbol{H}}_k$, which will exist only in the case of the number of total transmit antennas is no smaller than the number of total receive antennas. Consequently, this will introduce a constraint on the maximum number of users that can be served simultaneously in a cluster:

$$M_{\max} \leqslant \left\lfloor \frac{Nn_{\mathrm{T}}}{m_{\mathrm{R}}} \right\rfloor, \quad (4)$$

where $\lfloor x \rfloor$ denotes the maximum integer no bigger than x.

The principle of BD algorithm is to find the precoding matrix $\boldsymbol{W}_k$ using SVD to calculate the null space of $\overline{\boldsymbol{H}}_k$; the SVD of $\overline{\boldsymbol{H}}_k$ is defined as

$$\overline{\boldsymbol{H}}_k = \overline{\boldsymbol{U}}_k \begin{bmatrix} \overline{\boldsymbol{\Sigma}}_k & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \overline{\boldsymbol{V}}_k^{(1)} & \overline{\boldsymbol{V}}_k^{(0)} \end{bmatrix}^{\mathrm{H}}, \quad (5)$$

where superscript H indicates the Hermitian transpose. $\overline{\boldsymbol{\Sigma}}_k$ is a $\overline{L}_k$ dimension diagonal matrix of nonzero singular values, where $\overline{L}_k = \mathrm{rank}(\overline{\boldsymbol{H}}_k)$. $\overline{\boldsymbol{V}}_k^{(1)}$ holds the singular vectors corresponding to nonzero singulars, and $\overline{\boldsymbol{V}}_k^{(0)}$ is related to zero singulars. Let $\overline{\boldsymbol{V}}_k^{(0,r_k)}$ denote the last r_k right singular vectors of $\overline{\boldsymbol{V}}_k^{(0)}$. Thus, $\boldsymbol{W}_{k\_\mathrm{TPC}} = \overline{\boldsymbol{V}}_k^{(0,r_k)}$ forms an orthogonal basis for the null space of $\overline{\boldsymbol{H}}_k$ and subjects to the zero multi-user interference constraint. The total transmit power constraint can be denoted as

$$\begin{cases} \sum_{k=1}^{M} \mathrm{trace}\left(\boldsymbol{W}_{k\_\mathrm{TPC}} \boldsymbol{Q}_k \boldsymbol{W}_{k\_\mathrm{TPC}}^{\mathrm{H}}\right) \leqslant P_{\mathrm{sum}}, \\ \boldsymbol{Q}_k \geqslant 0, \end{cases} \quad (6)$$

where $\boldsymbol{Q}_k = \mathrm{E}\{\boldsymbol{S}_k \boldsymbol{S}_k^{\mathrm{H}}\}$ represents the $r_k \times r_k$ input covariance matrix of user k, and P_{sum} is the total transmit power.

Therefore, the achievable throughput is [9]

$$R_{\mathrm{TPC}} = \max_{\boldsymbol{Q}_k:(6)} \sum_{k=1}^{M} \log_2 \det \left(\boldsymbol{I}_{m_{\mathrm{R}}} + \frac{1}{\sigma_n^2} \boldsymbol{H}_k \boldsymbol{W}_{k\_\mathrm{TPC}} \boldsymbol{Q}_k (\boldsymbol{H}_k \boldsymbol{W}_{k\_\mathrm{TPC}})^{\mathrm{H}} \right). \quad (7)$$

The solution to the throughput maximization problem is to choose the precoding matrix as the right singular vectors of $\boldsymbol{H}_k \overline{\boldsymbol{V}}_k^{(0,r_k)}$ and perform water-filling power allocation [9].

However, the rest columns of $\overline{\boldsymbol{V}}_k^{(0)}$ except $\overline{\boldsymbol{V}}_k^{(0,r_k)}$ can be interpreted as the remaining spatial dimensions to support spatial diversity for user k, and $\boldsymbol{H}_k \overline{\boldsymbol{V}}_k^{(0)}$ is adopted to represent the parallel single user channel. Denote the SVD of the effective channel matrix $\boldsymbol{H}_k \overline{\boldsymbol{V}}_k^{(0)}$ as

$$\boldsymbol{H}_k \overline{\boldsymbol{V}}_k^{(0)} = \boldsymbol{U}_k \begin{bmatrix} \boldsymbol{\Sigma}_k & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{V}_k^{(1)} & \boldsymbol{V}_k^{(0)} \end{bmatrix}^{\mathrm{H}}, \quad (8)$$

where $\boldsymbol{\Sigma}_k$ is an $L_k = \mathrm{rank}\left(\boldsymbol{H}_k \overline{\boldsymbol{V}}_k^{(0)}\right)$ dimension diagonal matrix of nonzero singular values, and $\boldsymbol{V}_k^{(1)}$ holds the first L_k singular vectors. Let $\boldsymbol{V}_k^{(1,r_k)}$ denote the first r_k right singular vectors of $\boldsymbol{V}_k^{(1)}$ to support r_k independent data streams for the kth user. Therefore, the product of $\overline{\boldsymbol{V}}_k^{(0)}$ and $\boldsymbol{V}_k^{(1,r_k)}$ gives the precoding matrix that maximizes the data rate for user k as well as subjects to the zero multi-user interference constraint. The precoding matrix under TPC can be rewritten as

$$\boldsymbol{W}_{k\_\mathrm{TPC}} = \overline{\boldsymbol{V}}_k^{(0)} \boldsymbol{V}_k^{(1,r_k)}. \quad (9)$$

4 Power allocation algorithm

Since $\boldsymbol{V}_k^{(1)}$ is a unitary matrix, the transmit power of each user remains unchanged after precoding, which makes single-cell multi-user BD a reasonable algorithm to improve system performance compared with single-user MIMO.

$$\sum_{k=1}^{M} \mathrm{trace}(\boldsymbol{W}_{k\_\mathrm{TPC}} \boldsymbol{Q}_k \boldsymbol{W}_{k\_\mathrm{TPC}}^{\mathrm{H}}) = \sum_{k=1}^{M} \mathrm{trace}(\boldsymbol{Q}_k). \quad (10)$$

However, this is not sufficient for multi-cell coordinated transmission since the sum power of each eNB may exceed the maximum while transmitting multiple users' data with different precoding weights. Therefore, we define the BD precoding matrix associated with the bth eNB under PePC as

$$\boldsymbol{W}_{b\_\mathrm{PePC}} \in \mathcal{C}^{n_{\mathrm{T}} \times \sum_{k=1}^{M} r_k} \quad (1 \leqslant b \leqslant N) \cdot$$

The transmit power constraint for the bth eNB can be expressed as

$$\mathrm{trace}(\boldsymbol{W}_{b\_\mathrm{PePC}} \boldsymbol{Q} \boldsymbol{W}_{b\_\mathrm{PePC}}^{\mathrm{H}}) \leqslant \frac{P_{\mathrm{sum}}}{N}, \quad (11)$$

where $\boldsymbol{Q} = \mathrm{blockdiag}\{\boldsymbol{Q}_1 \quad \boldsymbol{Q}_2 \quad \cdots \quad \boldsymbol{Q}_M\}$.

To guarantee the transmit power of each eNB remains the same after precoding, the following equation needs to be fulfilled:

$$\mathrm{trace}(\boldsymbol{W}_{b\_\mathrm{PePC}} \boldsymbol{Q} \boldsymbol{W}_{b\_\mathrm{PePC}}^{\mathrm{H}}) = \mathrm{trace}(\boldsymbol{Q}). \quad (12)$$

Thus, we define the simple combined precoding and power allocation matrix for the bth eNB to satisfy the PePC as

$$\boldsymbol{W}_{b\_\mathrm{PePC}} = \hat{\boldsymbol{D}}_b \hat{\boldsymbol{W}}_b, \tag{13}$$

where

- $\hat{\boldsymbol{W}}_b$ represents the precoding weights for the bth eNB under TPC, which includes n_T row vectors of $\boldsymbol{W}$.

$$\begin{aligned}\boldsymbol{W} &= \left[\boldsymbol{W}_{1\_\mathrm{TPC}}\ \boldsymbol{W}_{2\_\mathrm{TPC}}\ \cdots\ \boldsymbol{W}_{M\_\mathrm{TPC}}\right]\\ &= \left[\hat{\boldsymbol{W}}_1^\mathrm{T}\ \hat{\boldsymbol{W}}_2^\mathrm{T}\ \cdots\ \hat{\boldsymbol{W}}_N^\mathrm{T}\right]^\mathrm{T};\end{aligned} \tag{14}$$

- $\hat{\boldsymbol{D}}_b$ is the power normalization matrix for the bth eNB and can be denoted as

$$\hat{\boldsymbol{D}}_b = \frac{1}{\left\|\hat{\boldsymbol{W}}_b\right\|_\mathrm{F}} \times \boldsymbol{I}_{n_\mathrm{T}}, \tag{15}$$

where $\|\cdot\|_\mathrm{F}$ denotes the Frobenius norm. Therefore, the power of each eNB remains the same after joint transmission using $\boldsymbol{W}_{b\_\mathrm{PePC}}$ as the precoding matrix, which makes the capacity gains achieved by the multi-cell collaboration reasonable.

5 Simulation results

5.1 Simulation assumptions

In this section, the performance of the proposed power allocation scheme is evaluated by system level simulation. Assume that each cell is divided into three sectors and two different cluster configurations are applied, where windmill cluster consists of three sectors belonging to different cells, and hexagonal cluster is composed of three sectors belonging to the same cell. The sectors in the same color shown in Fig. 2 compose a coordination cluster, where $N = M = 3$, $n_\mathrm{T} = 4$ and $m_\mathrm{R} = 2$. UEs can adaptively choose single or dual streams according to the maximal throughput principle. Maximal ratio combining (MRC) and minimum mean square error (MMSE) receivers are adopted to demodulate the transmitted signal vectors for single and dual streams, respectively.

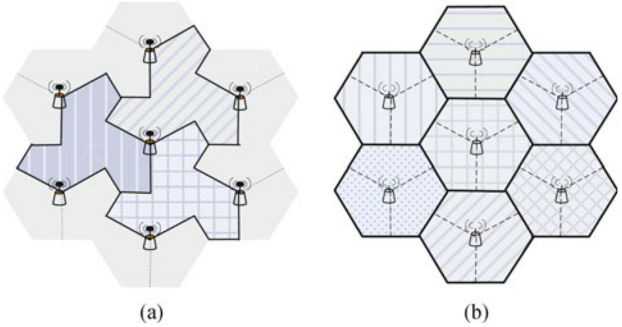
(a)
(b)

Fig. 2 System layout of coordination clusters. (a) Windmill cluster; (b) hexagonal cluster

Although water-filling maximize the sum rate, it may result in some weaker users with no or very little throughput, and the system is unfair to that kind of users. Thus, we assume that each independent input data stream has equal power. The proposed scheme can be implemented with any specific scheduling algorithm. To reduce the complexity and achieve fairness among users, proportional fair (PF) scheduling [11] method is applied. The minimum unit for resource allocation based on orthogonal frequency division multiplexing access - time-division duplexing (OFDMA-TDD) frame structure is one RB, which composed of 12 consecutive subcarriers in the frequency domain and 7 OFDM symbols in the time domain [12]. The detailed simulation parameters are listed in Table 1.

Table 1 Simulation parameters

parameters	value
layout	3-sectorized hexagonal grid with seven cells and wrap-around
carrier frequency	2 GHz
ISD	500 m
bandwidth	10 MHz
FFT size	1024
number of subcarriers available	600
DL/UL ratio	2DL/2UL
special subframe	[10:2:2] for DwPTS, GP, and UpPTS
eNB max transmission power	46 dBm
average number of users per sector	10
traffic model	full buffer
UE speed	3 km/h
lognormal shadowing	Gaussian distribution with 0 mean, 8 dB standard deviation
penetration loss	20 dB
path loss	$128.1 + 37.6\lg d$ (d in km)
channel model	SCM-E
BLER target	10%

5.2 Spectrum efficiency

The downlink spectrum efficiency (SE, in bps/Hz/sector) results are presented in Table 2, where the cell-edge user throughput is defined as the fifth percentile point of the cumulative distribution function (CDF) of users average packet throughput.

Compared to BD with TPC, in coordination windmill cluster, the proposed BD with PePC scheme only decreases the downlink average cell SE and cell-edge user SE by 0.64% and 7.46%. In the coordination hexagonal cluster, the average cell SE is increased by 0.92%, while cell-edge user SE is decreased by 0.6%. From this, we can see that the proposed algorithm performs very close to BD with

Table 2 Downlink spectrum efficiency

		average cell SE	cell-edge user SE
coordination windmill cluster	BD with TPC	2.30	0.078
	BD with PePC	2.29	0.072
coordination hexagonal cluster	BD with TPC	3.42	0.083
	BD with PePC	3.46	0.082

TPC and has more reality.

In addition, the hexagonal cluster has larger average cell SE and cell-edge user SE compared with windmill cluster. Moreover, hexagonal cluster does not need intercell signaling through air interface or fiber, which makes it a practical scheme used in LTE-Advanced system. Therefore, we propose to use hexagonal cluster instead of windmill one.

5.3 Average user SINR

The CDF curves of the average user signal to interference and noise ratio (SINR) are illustrated in Fig. 3 for downlink, where cluster-a) indicates the coordination windmill cluster and cluster-b) represents the coordination hexagonal cluster.

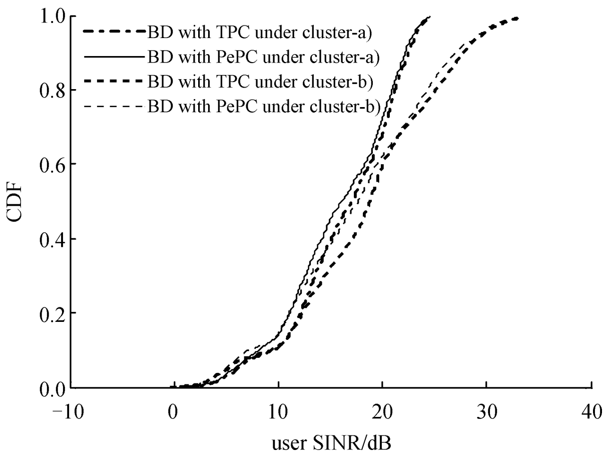

Fig. 3 CDF curves of received user SINR

In Fig. 3, it can be seen that the SINR of BD with PePC is very close to that of BD with TPC under both coordination clusters. In addition, the SINR of coordination hexagonal cluster is larger than that of windmill cluster with maximum 7 dB gain.

6 Conclusion

In this paper, we analyze the power allocation algorithm under PePC for the downlink of multi-cell BD based coordinated transmission system. We explain that it is no longer practical to use BD algorithm with TPC in coordinated LTE-Advanced system, for each eNB transmits multiple users' data with different precoding weights in a resource block simultaneously, which may cause the transmit power per eNB exceed the limit. Consequently, we propose a power allocation algorithm combined with BD precoder to meet the constraint. It is proved that the proposed BD with PePC approach has both reality and near-optimal performance by system level simulation.

Acknowledgements This work was supported by the Research Institution of China Mobile.

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