ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/282029805

Energy-Efficient Precoded Coordinated Multi-Point Transmission With Pricing Power Game Mechanism

Article *in* IEEE Systems Journal · June 2017

DOI: 10.1109/JSYST.2015.2464218

CITATION
1

READS
55

4 authors:

Shu Fu
Chongqing University
17 PUBLICATIONS **75** CITATIONS
SEE PROFILE

Hong Wen
University of Texas MD Anderson Cancer Center
96 PUBLICATIONS **1,170** CITATIONS
SEE PROFILE

Jinsong Wu
University of Chile
138 PUBLICATIONS **891** CITATIONS
SEE PROFILE

Bin Wu
Tianjin University
92 PUBLICATIONS **704** CITATIONS
SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Project YEATS domain and histone acylation View project

Project BRIGHT - Bringing 5G Connectivity in Rural and Low-Income Areas View project

All content following this page was uploaded by Jinsong Wu on 23 November 2017.

The user has requested enhancement of the downloaded file.

Energy-Efficient Precoded Coordinated Multi-Point Transmission With Pricing Power Game Mechanism

Shu Fu, Hong Wen, Jinsong Wu, *Senior Member, IEEE*, and Bin Wu, *Member, IEEE*

***Abstract*—The coordinated multiple-point (CoMP) transmission technique recently has been considered as an efficient method to achieve energy-efficient cellular wireless communications and enhance cell-edge user performance. Conventional energy-efficient power allocation in CoMP is based simply on water filling (WF) without considering frequency diversity (different base station clustering and user scheduling results in each subband). For the single-antenna scenario without the involvement of precoding, we have recently proposed a noncooperative power game (PG) mechanism with pricing for power allocation as an interference coordination method to improve energy efficiency and throughput performance. In this paper, we generalize the noncooperative pricing game mechanism with pricing across both frequency and space in the scenario of multiuser multiple-input–multiple-output-based CoMP transmissions. First, a block diagonalization precoding-based CoMP transmission system is reformulated as multiple single-antenna transmit–receive pairs from a viewpoint of streams. Second, taking frequency diversity into account, we propose a novel WF power-allocation algorithm to provide the power strategy space (the range of power of streams), based on which PG in each stream is further proposed. Thus, the noncooperative PG with pricing can be executed in all streams. Extensive simulation results then demonstrate the effectiveness of the new proposal.**

***Index Terms*—Coordinated multiple point (CoMP), frequency diversity, interference coordination, pricing power game (PG).**

I. INTRODUCTION

WITH multiuser multiple-input–multiple-output (MU-MIMO) wireless transmission, a base station (BS) can serve multiple users simultaneously at the same frequency in a mobile cellular communication system, where user throughput can be largely improved. However, users with low single-cell signal-to-interference-plus-noise ratio (SINR), defined as edge users, still suffer serious intercell interference (ICI). Coordinated multiple-point (CoMP) transmission has been considered as a key technique to mitigate serious ICI between edge users for the recent 4G [1]–[6] and 5G [7] wireless communication systems to enhance the user throughput and energy efficiency.

A wireless frequency bandwidth can be equally divided into multiple subbands, which is defined as frequency diversity. Frequency diversity is used to improve system performance in frequency-selective channels. In CoMP systems, BSs are grouped as several coordination BS sets (CBSs) independently, which are also defined as *clusters*. CBS plays as a super BS serving a set of edge users in the coverage of the BSs. This CBS grouping process is defined as transmission scheduling. Transmission scheduling can be determined by traffic quality of service using static [8]–[10] or dynamic [1]–[3] methods. Although CoMP can transform a wireless interference channel into an aimed signal channel via transmission scheduling, interference for edge users is still large and both the user throughput and energy efficiency may be poor [1]–[3]. In this paper, we intend to further improve user throughput and energy efficiency by interference coordination via a power game (PG) with pricing between different CBS.

Noncooperative game is a critical interference coordination method to enhance energy efficiency and user throughput [1], [11]–[15], where the user throughput can be improved as power decreases. The works in [14] and [15] treated interferences as Gaussian white noises and further propose the iterative water-filling (IWF) PG. However, the convergence condition of the algorithms cannot be guaranteed in a distributed manner. In our recent work [1], we have proposed a PG with pricing in CoMP, which suggests that certain power deduction can improve both energy efficiency and user throughput. However, only a single-antenna scenario without the involvement of precoding is assumed in [1].

Two general issues in interference coordination prevent our PG framework in [1] from being directly applied to a multi-antenna scenario: 1) initial water-filling (WF) power allocation in multiple frequency subbands for CoMP transmission remains unexploited; and 2) power reallocation of the remaining power after the PG mechanism with pricing in block diagonalization (BD) precoding-based MU-MIMO.

For the first issue, BSs of a CBS in a specific subband can simultaneously send aimed signals to a set of edge users. However, due to power constraint on each BS and frequency diversity, some specific characteristics must be considered. *First*, BD precoding is jointly executed by all transmit antennas of BSs in the same CBS. Therefore, the power proportion of each stream taken by BSs in its CBS is determined by BD precoding. *Second*, since frequency diversity supports different streams served by a BS in different subbands, arbitrary BS belongs to a

---

Manuscript received November 22, 2014; revised March 15, 2015 and July 4, 2015; accepted July 26, 2015. Date of publication August 31, 2015; date of current version June 26, 2017. This work was supported in part by the 863 High-Technology Plan under Grant 2015AA01A707 and in part by China Scholarship Council Program.

S. Fu is with the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, Chengdu 611731, China, and also with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: fshfshu@aliyun.com).

H. Wen is with the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, Chengdu 611731, China (e-mail: sunlike@uestc.edu.cn).

J. Wu is with the Department of Electrical Engineering, Universidad de Chile, 8370451 Santiago, Chile (e-mail: wujs@ieee.org).

B. Wu is with the School of Computer Science and Technology, Tianjin University, Tianjin 300072, China (e-mail: binwu.tju@gmail.com).

Digital Object Identifier 10.1109/JSYST.2015.2464218

1937-9234 © 2015 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

different CBS in each subband. Zhang *et al.* in [8] consider WF power allocation for CoMP transmission but only in flat-fading channels. Our latest work [1] has taken frequency diversity into account in frequency-selective channels in CoMP, but the approach was based on a single-antenna scenario without precoding. For the second issue, the pricing game mechanism has been proposed in our work [1] under a single-antenna scenario without precoding. This largely limits antenna space diversity gain in CoMP transmission. Therefore, extending the mechanism in [1] into a MU-MIMO-based CoMP scenario is promising.

Motivated by the above observations, we propose a novel WF power-allocation algorithm with frequency diversity (WFFD) based on a stream analytical model to acquire the initial power in each stream. Moreover, a PG mechanism with pricing is applied to execute interference coordination between streams in order to improve energy efficiency and throughput in MU-MIMO-based CoMP. Unlike the conventional WF scheme in CoMP proposed by Zhang *et al.* in [8] working only on flat-fading channels, in this paper, we first propose the WF algorithm with the use of frequency diversity in CoMP for frequency-selective selective channels. The *scaled WF* algorithm in [8] executes WF once only, and the value of the reduced power consumption per BS for BD precoding cannot be reused again. The WFFD algorithm proposed in our work can reuse the value of the reduced power consumption and reperform WF in iteration until all streams have reached the maximum power by WF with BD precoding.

The *maximum CBS size* (i.e., the maximum number of BSs in a CBS) is denoted as $m_{\max}$. We assume that the transmission scheduling in each subband has been predetermined by some appropriate algorithm. Based on the coordination relationship of BSs determined by CBSs, BD precoding is executed and multiple parallel streams are generated in each CBS. We study the system from the viewpoint of streams, where each stream can be equivalent to a single-antenna transmit–receive pairs (called a stream model). The power pumped in a stream is contributed by the BSs in its CBS with power proportion determined by BD. On the other hand, an arbitrary BS can serve for multiple streams in different CBSs. The two features are considered in the WF-based power allocation for CoMP transmission, and a novel IWF algorithm is proposed.

To take the pricing game-based interference coordination into account, by employing the stream model, the power strategy space (the range of power of stream) of each stream can be provided via WFFD. Based on the power strategy space of each stream, the pricing game for single-antenna CoMP in [1] can be directly used to adjust the initial power.

The remainder of the paper is organized as follows. Section II sketches the system model and outlines the top-level algorithm philosophy to achieve higher energy efficiency in the discussed wireless communication system. A novel stream analysis model to transform the MIMO-based CoMP transmission into multiple virtual single-antenna transmit–receive pairs is proposed in Section III. Section IV provides a WF and equal power allocation (EPA) power-allocation algorithm with the support of frequency diversity in CoMP transmission. The pricing PG mechanism is further applied to adjust the initial WF power of each stream in Section V. Section VI presents numerical results. Finally, we conclude this paper in Section VII.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

In this paper, we focus on the downlink CoMP with joint transmission mode of the joint processing. Frequency reuse factor is set to one to improve the spectrum efficiency. m BSs ($\boldsymbol{m} = \{1, 2, \ldots, m\}$) exist in the system. It is assumed that both BSs and users are equipped with N_t and N_r antennas, respectively, for transmission and reception. For simplicity, we assume that N_r streams are transmitted to each of the scheduled cell edge users, where $N_t \geq N_r$ is guaranteed. Bandwidth B is equally divided into i orthogonal subbands $\boldsymbol{i} = \{1, 2, \ldots, i\}$, in each of which transmission scheduling is self-governed. We assume that transmission scheduling result in each subband motivated for better energy efficiency has been predetermined with the constraint of the maximum number of BSs in a CBS $m_{\max}$. Each BS costs a fixed circuit power C. Like in [14], we assume interference of each user as white Gaussian noise to simplify the system model.

Given that the transmission scheduling results in subbands have been provided by a predecided algorithm, an arbitrary BS is partitioned into a specific CBS in different subbands. Then, two limitation conditions of power allocation in CoMP can be described as follows.

C_1 All antennas of BSs in the same CBS jointly execute BD precoding to transmit multiple parallelized streams to a set of edge users in the coverage of the CBS.

C_2 With the BD precoding result, power proportion of BSs serving for a stream can be determined. We assume that the BS total power is $P_{\max}$; given that arbitrary BS m has pumped its total power $P_{\max}$ to its serving streams, power allocation of all streams in BS m will be terminated to remain the power proportion in BD precoding.

B. Problem Formulation

Consider a particular subband $i \in \boldsymbol{i}$. Let $\boldsymbol{k}_i = \{1, 2, \ldots, |\boldsymbol{k}_i|\}$ denote the cluster set in subband i and $\boldsymbol{m}_{i,k} = \{1, 2, \ldots, |\boldsymbol{m}_{i,k}|\}$ denote the BS set of clusters k in subband i. For an arbitrary BS $m \in \boldsymbol{m}$, let $\boldsymbol{u}_{i,k}$ denote the scheduled edge user set of clusters k in subband i, and $\boldsymbol{s}^u_{i,k}$ denotes the $N_r \times 1$ transmitted stream vector of user u in cluster k in subband i, where $|\boldsymbol{s}^u_{i,k}| = N_r$. Then, the transmitted stream vector of cluster k in subband i is formulated as

$$\boldsymbol{s}_{i,k} = \left[\boldsymbol{s}^{1}_{i,k}{}^{H}, \boldsymbol{s}^{2}_{i,k}{}^{H}, \ldots, \boldsymbol{s}^{|\boldsymbol{u}_{i,k}|}_{i,k}{}^{H} \right]^{H}. \tag{1}$$

Like in [8], for arbitrary cluster k in subband i, the largest number of edge users scheduled in cluster k, $|\boldsymbol{u}_{i,k}|_{\text{largest}}$, is

$$|\boldsymbol{u}_{i,k}|_{\text{largest}} = \left\lfloor \frac{N_t \times |\boldsymbol{m}_{i,k}|}{N_r} \right\rfloor. \tag{2}$$

Let $\boldsymbol{H}^i_{u,m}$ denote the $N_r \times N_t$ channel matrix from BS m to user u. Then, in an arbitrary subband i, the channel matrix from BSs of cluster k to user u is

$$\boldsymbol{H}^i_{u,k} = \left[\boldsymbol{H}^i_{u,\boldsymbol{m}_{i,k}(1)}, \boldsymbol{H}^i_{u,\boldsymbol{m}_{i,k}(2)}, \ldots, \boldsymbol{H}^i_{u,\boldsymbol{m}_{i,k}}(|\boldsymbol{m}_{i,k}|) \right]. \tag{3}$$

Let $\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(s)}$ be the $(|\boldsymbol{m}_{i,k}| \times N_t) \times 1$ transmit precoder vector of the sth stream of user u in cluster k in subband i, where $1 \leq s \leq N_r$. Without loss of generality, we assume that $\mathbb{E}[\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(s)} \ \boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(s)^H}] = \mathbf{I}_{(|\boldsymbol{m}_{i,k}| \times N_t)}$, where $\mathbf{I}_{(|\boldsymbol{m}_{i,k}| \times N_t)}$ represents an $(|\boldsymbol{m}_{i,k}| \times N_t) \times (|\boldsymbol{m}_{i,k}| \times N_t)$ identity matrix. Given that edge user u is in the coverage of cluster k in subband i, then the $(|\boldsymbol{m}_{i,k}| \times N_t) \times N_r$ transmit precoder matrix of cluster k to user u in subband i is

$$\boldsymbol{T}_{i,k}^{u} = \left[\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(1)}, \boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(2)}, \ldots, \boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(N_r)}\right]. \quad (4)$$

By (4), $\boldsymbol{T}_{i,k}^{\boldsymbol{u}_{i,k}(a)}$ represents the $(|\boldsymbol{m}_{i,k}| \times N_t) \times N_r$ transmit precoder matrix of cluster k to the ath user in $\boldsymbol{u}_{i,k}$ in subband i; then, the $(|\boldsymbol{m}_{i,k}| \times N_t) \times (|\boldsymbol{u}_{i,k}| \times N_r)$ transmit precoder matrix of cluster k to all streams of scheduled edge users in cluster k in subband i is

$$\boldsymbol{T}_{i,k} = \left[\boldsymbol{T}_{i,k}^{\boldsymbol{u}_{i,k}(1)}, \boldsymbol{T}_{i,k}^{\boldsymbol{u}_{i,k}(2)}, \ldots, \boldsymbol{T}_{i,k}^{\boldsymbol{u}_{i,k}(|\boldsymbol{u}_{i,k}|)}\right]. \quad (5)$$

Let $\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s)}$ denote the $(|\boldsymbol{m}_{i,k}| \times N_t) \times 1$ transmit precoder vector of the sth stream in cluster k in the ith subband, which is corresponding to the sth column of $\boldsymbol{T}_{i,k}$.

Let $\boldsymbol{Q}_{i,k}^{u}$ denote the transmit covariance matrix of user u in cluster k in subband i, where $\boldsymbol{Q}_{i,k}^{u} = \mathbb{E}[\boldsymbol{T}_{i,k}^{u} \boldsymbol{s}_{i,k}^{u} {\boldsymbol{s}_{i,k}^{u}}^H {\boldsymbol{T}_{i,k}^{u}}^H]$. Likewise, let $\boldsymbol{Q}_{i,k} = \mathbb{E}[\boldsymbol{T}_{i,k} \boldsymbol{s}_{i,k} {\boldsymbol{s}_{i,k}}^H {\boldsymbol{T}_{i,k}}^H]$ represent the transmit covariance matrix of cluster k to all users in it in subband i.

Under BD precoding, each user will filter the intracluster (in the cluster) interference by a receive precoder matrix. For arbitrary user u in cluster k in subband i, the s-stream, where $1 \leq s \leq N_r$, of the user has a $1 \times N_r$ receive precoder vector $\boldsymbol{v}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(s)}$. Then, the $N_r \times N_r$ receive precoder matrix of cluster k to user u on subband i is

$$\boldsymbol{V}_{i,k}^{u} = \left[\boldsymbol{v}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(1)^H}, \boldsymbol{v}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(2)^H}, \ldots, \boldsymbol{v}_{i,k}^{\boldsymbol{s}_{i,k}^{u}(N_r)^H}\right]^H. \quad (6)$$

Like in (5), the $(|\boldsymbol{u}_{i,k}| \times N_r) \times N_r$ receive precoder matrix of cluster k to all the streams of edge users in cluster k on subband i is

$$\boldsymbol{V}_{i,k} = \left[\boldsymbol{V}_{i,k}^{\boldsymbol{u}_{i,k}(1)^H}, \boldsymbol{V}_{i,k}^{\boldsymbol{u}_{i,k}(2)^H}, \ldots, \boldsymbol{V}_{i,k}^{\boldsymbol{u}_{i,k}(|\boldsymbol{u}_{i,k}|)^H}\right]^H. \quad (7)$$

Let $\boldsymbol{v}_{i,k}^{\boldsymbol{s}_{i,k}(s)}$ denote the $1 \times N_r$ transmit precoder vector of the sth stream in cluster k on the ith subband, which is corresponding to the sth row of $\boldsymbol{V}_{i,k}$.

The specific BD precoder for BSs and users can be obtained from singular value decomposition. The detailed introduction to BD precoding can be found in [8].

The additive white Gaussian noise, denoted as $\tilde{n}$, for arbitrary edge user has zero mean and variance $\mathbb{E}(\tilde{n}\tilde{n}^H) = \sigma^2 I_{N_r}$, where I_{N_r} is an $N_r \times N_r$ unit matrix. For arbitrary scheduled edge user u of cluster k in the ith subband with frequency diversity, the interference will be nulled in different subbands and as intraclusters. Let $R_{i,k}^{u}(-\boldsymbol{Q}_{i,k}^{u})$ represent

$$R_{i,k}^{u}\left(-\boldsymbol{Q}_{i,k}^{u}\right) = \Sigma_{\substack{k' \in \boldsymbol{k}_i \\ k' \neq k}} H_{u,k'}^{i} (\boldsymbol{Q}_{i,k}) {H_{u,k'}^{i}}^H + \sigma^2 I_{N_r} \quad (8)$$

the covariance matrix of interference plus noise of user u of cluster k in subband i.

Therefore, with BD precoding, the achievable data rate in CoMP R_{CoMP} can be formulated as follows:

$$R_{\text{Comp}} = \Sigma_{i \in \boldsymbol{i}} \Sigma_{k \in \boldsymbol{k}_i} \Sigma_{u \in \boldsymbol{u}_{i,k}} \times \log\left|I + {H_{u,k}^{i}}^H \left(R_{i,k}^{u}\left(-\boldsymbol{Q}_{i,k}^{u}\right)\right)^{-1} H_{u,k}^{i}\right| \quad (9)$$

subject to conditions C_1 and C_2 described in Section II-A.

The system model in (9) is created based on some matrix analysis theorems, where the noncooperative game framework is difficult to be built up. For example, in [16], a complicated orthogonal projection theorem was involved to prove the existence and uniqueness of a game theorem.

III. STREAM ANALYSIS MODEL

From the viewpoint of streams, in an arbitrary cluster k, we have $\mathbb{E}(\tilde{n}\tilde{n}^H) = \sigma^2 I_{|u_{i,k}|N_r}$. In the ith subband, for an arbitrary stream s and s', where $1 \leq s \leq |\boldsymbol{s}_{i,k}|$ and $1 \leq s' \leq |\boldsymbol{s}_{i,k'}|$, we assume that stream $\boldsymbol{s}_{i,k}(s)$ belongs to the edge user $\boldsymbol{u}_{i,k}(u)$ in cluster k and stream $\boldsymbol{s}_{i,k'}(s')$ belongs to the edge user $\boldsymbol{u}_{i,k'}(u')$ in cluster k', respectively. Then, the sth stream in cluster $k \in \boldsymbol{k}_i$ to the s'th stream in cluster $k' \in \boldsymbol{k}_i$ will go through the transmit precoder $\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s)}$, channel $\boldsymbol{H}_{\boldsymbol{u}_{i,k'(u'),k}}^{i}$, and receive precoder $\boldsymbol{v}_{i,k'}^{\boldsymbol{s}_{i,k'}(\boldsymbol{s}')}$. The equivalent channel from stream s to s' is

$$\widetilde{H}_{\boldsymbol{s}_{i,k'}(s'),\boldsymbol{s}_{i,k}(s)}^{i} = \boldsymbol{v}_{i,k'}^{\boldsymbol{s}_{i,k'}(s')} \times \boldsymbol{H}_{\boldsymbol{u}_{i,k'}(u'),k}^{i} \times \boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s)}. \quad (10)$$

With BD precoding, the intracluster interference will be filtered by the transmit precoder at the BSs of the cluster and the receive precoder at the edge user. Therefore, we have

$$\widetilde{H}_{\boldsymbol{s}_{i,k'}(s'),\boldsymbol{s}_{i,k}(s)}^{i} = 0, \quad k = k', \text{ and } s \neq s'. \quad (11)$$

With this transformation, the multiple-antenna CoMP system is equivalent to a multiple-stream-based single-antenna system with the equivalent channel in (10).

After BD precoding, the power-allocation strategy for streams in cluster k in subband i is denoted as an $s \times s$ diagonal matrix $\boldsymbol{D}_{i,k}$. The sum of the noise and the interference from streams in other clusters to the sth stream in cluster k in the ith subband is

$$Z_{i,k}^{\boldsymbol{s}_{i,k}(s)} = \sigma^2 + \Sigma_{\substack{k' \in \boldsymbol{k}_i \\ k' \neq k}} \Sigma_{s' \in \left[1:|\boldsymbol{s}_{i,k'}|\right]} \boldsymbol{D}_{i,k'}(s', s') \times \widetilde{H}'_{\boldsymbol{s}_{i,k}(s),\boldsymbol{s}_{i,k'}(s')} \times \left(\widetilde{H}_{\boldsymbol{s}_{i,k}(s),\boldsymbol{s}_{i,k'}(s')}^{i}\right)^H \quad (12)$$

where $Z_{i,k}^{\boldsymbol{s}_{i,k}(s)}$ is the covariance of the interference plus noise of the sth stream in cluster k in subband i, which can be estimated at the edge user, where the stream belongs to. Many methods discussed in [8], such as silent period of the desired signal, the pilot signal, and blind estimation, can be used to perform this estimation.

The received intended information for the sth stream in cluster k on the ith subband is

$$G_{i,k}^{\boldsymbol{s}_{i,k}(s)} = \boldsymbol{D}_{i,k}(s,s) \times \widetilde{H}_{\boldsymbol{s}_{i,k}(s),\boldsymbol{s}_{i,k}(s)}^{i} \times \left(\widetilde{H}_{\boldsymbol{s}_{i,k}(s),\boldsymbol{s}_{i,k}(s)}^{i}\right)^H. \quad (13)$$

Therefore, the throughput of the sth stream in cluster k in the ith subband is

$$r_{i,k}^{s} = \frac{B}{|\boldsymbol{i}|} \log_2 \left(1 + \frac{G_{i,k}^{\boldsymbol{s}_{i,k}(s)}}{Z_{i,k}^{\boldsymbol{s}_{i,k}(s)}} \right). \tag{14}$$

The throughput of each stream in (14) is subjected to the power-allocation fraction factor of each BS serving it, as well as the constraint of the overall power per BS.

In (5), for an arbitrary s, $1 \le s \le |\boldsymbol{s}_{i,k}|$, the $(|\boldsymbol{m}_{i,k}| \times N_t) \times 1$ transmit precoder vector of the sth stream in cluster k in the ith subband is $\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s)}$, where the transmit precoder vector of the mth BS in $\boldsymbol{m}_{i,k}$ to stream $\boldsymbol{s}_{i,k}(s)$ is composed by the vector

$$\begin{aligned} &\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s),\boldsymbol{m}_{i,k}(m)} \\ &\quad= \Big[\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s)} \left((m-1) \times N_t + 1\right)^H \boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s)} \\ &\qquad \times \left((m-1) \times N_t + 2\right)^H, \ldots, \boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s)} \\ &\qquad \times \left((m-1) \times N_t + N_t\right)^H \Big]^H. \end{aligned} \tag{15}$$

Let $\|\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s),\boldsymbol{m}_{i,k}(m)}\|_2^2$ be the 2-norm of $\boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s)\boldsymbol{m}_{i,k}(m)}$; then, the power fraction of the mth BS in $\boldsymbol{m}_{i,k}$ to $\boldsymbol{s}_{i,k}(s)$ is

$$F_{i,k}^{\boldsymbol{s}_{i,k}(s),\boldsymbol{m}_{i,k}(m)} = \left\| \boldsymbol{t}_{i,k}^{\boldsymbol{s}_{i,k}(s),\boldsymbol{m}_{i,k}(m)} \right\|_2^2 \tag{16}$$

where $F_{i,k}^{\boldsymbol{s}_{i,k}(s),\boldsymbol{m}_{i,k}(m)}$ denotes the power proportion that the mth BS in $\boldsymbol{m}_{i,k}$ takes in $\boldsymbol{D}_{i,k}(s,s)$.

From the viewpoint of streams, each BS serves multiple streams and the power of each stream is contributed by multiple BSs according to the proportion in (16). For simplicity, we ignore the cluster and subband index that each stream belongs to and observe the system from the viewpoint of streams. Let $\boldsymbol{s}_m$ be the set containing all the streams that BS m serves over all the subbands, where $m \in \boldsymbol{m}$, and $\boldsymbol{m}_s$ be the BS set serving for the stream s, respectively. Then, we can rewrite (16) as

$$F_{m'}^{\boldsymbol{s}_{m'}(s')} = F_{i,k}^{\boldsymbol{s}_{i,k}(s),\boldsymbol{m}_{i,k}(m)} \tag{17}$$

where $m' = \boldsymbol{m}_{i,k}(m)$, and s' is the refined index of $\boldsymbol{s}_{i,k}(s)$ in s_m. Likewise, the power-allocation strategy for the sth stream in cluster k on subband i, $\boldsymbol{D}_{i,k}(s,s)$, is rewritten as

$$D_{s'} = \boldsymbol{Q}_{i,k}(s,s) \tag{18}$$

where $s' = \boldsymbol{s}_{i,k}(s)$. For an arbitrary stream $s \in \boldsymbol{s}_{i,k}$ in cluster k in the ith subband, let $\boldsymbol{s}_{\text{null}}^{s}$ denote the set of streams other than s in $\boldsymbol{s}_{i,k}$, as well as all the streams in subbands other than i. The interference from the streams in $\boldsymbol{s}_{\text{null}}^{s}$ to the stream s is null. Then, we can rewrite the equivalent channel in (10) and (11) as

$$\begin{aligned} \widetilde{H}_{s'_0,s_0} &= \widetilde{H}^{i}_{\boldsymbol{s}_{i,k'}(s'),\boldsymbol{s}_{i,k}(s)}, \text{ where } s'_0 = \boldsymbol{s}_{i,k'}(s'), \text{ and} \\ s_0 &= \boldsymbol{s}_{i,k}(s) \end{aligned} \tag{19}$$

$$\text{s.t. } \widetilde{H}_{s'_0,s_0} = 0, \quad \forall\, s'_0 \in \boldsymbol{s}_{\text{null}}^{s}. \tag{20}$$

With this definition, let $\boldsymbol{s}_{\text{all}}$ be the set of all streams in the system. Then, we can reformulate (12) and (13) as (21) and (22), respectively, as follows:

$$Z_s = \sigma^2 + \Sigma_{\substack{s' \in \boldsymbol{s}_{\text{all}} \\ s' \neq s \\ s' \notin \boldsymbol{s}_{\text{null}}^{s}}} D_s \times \widetilde{H}_{s,s'} \times \left(\widetilde{H}_{s,s'}\right)^H, \quad \forall\, s \tag{21}$$

$$G_s = D_s \times \widetilde{H}_{s,s} \times (\widetilde{H}_{s,s})^H, \quad \forall\, s. \tag{22}$$

With this discussion, the overall power of each BS is set to $P_{\max}$. For arbitrary stream s, the power of BS $m \in \boldsymbol{m}_s$ pumped into the stream is denoted as p_m^s. Therefore, let r_s be the throughput of each stream, then we can summarize the stream-based system model as

$$\sum_{s \in \boldsymbol{s}_{\text{all}}} r_s = \sum_{z \in \boldsymbol{s}_{\text{all}}} \frac{B}{|\boldsymbol{i}|} \log_2 \left(1 + \frac{G_s}{Z_s} \right) \tag{23}$$

$$\text{s.t. } D_s = \Sigma_{m \in \boldsymbol{m}_s} P_m^s, \quad \forall\, s \in \boldsymbol{s}_{\text{all}} \tag{24}$$

$$\frac{p_m^s}{D_s} = F_m^s, \quad \forall\, s \in \boldsymbol{s}_{\text{all}}, \text{ and } \forall\, m \in \boldsymbol{m}_s \tag{25}$$

$$\Sigma_{s \in \boldsymbol{s}_m} p_m^s \le P_{\max}, \quad \forall\, m \in \boldsymbol{m}. \tag{26}$$

With the stream-based model, we can easily decompose the complicated matrix analysis problem in (9) into multiple ordinary single-antenna transmit–receive pairs, where constraint conditions C_1 and C_2 are formulated as (24)–(26).

IV. WF WITH FREQUENCY DIVERSITY IN COMP

With the stream-based system model proposed in (21)–(24), subbands and clusters are transparent for BSs in each cluster. Each BS only concerns the streams the BS serves and the power proportion defined by (17). Therefore, each BS can perform WF-based power allocation on the streams it serves with the equivalent channel defined in (19). However, power allocation may violate the condition in (17) between BSs serving the same stream. Therefore, power adjustment is needed between BSs serving for the same stream. Thereafter, each BS will perform WF algorithm again with the power remaining in the last circulation. In this section, we design a power-allocation algorithm that works in a distributed fashion for intercluster (between clusters) BSs and in a centralized fashion for intracluster BSs.

A. WF-Based Power-Allocation Algorithm Description

In Section III, we construct a stream-based CoMP system with the support of frequency diversity, where each stream is equivalent to a single-antenna transmitter–receiver pair with the equivalent channel defined in (19). Due to the centralized structure intracluster, for an arbitrary stream, the BS power proportion in (17) is available for BSs serving the stream. Let $\boldsymbol{s}_m$ be the streams' list for BS m, $m \in \boldsymbol{m}$, where streams the BS serves are recorded. Likewise, $\boldsymbol{m}_s$ (BSs set serving stream s) and the BS power proportion F_m^s are recorded at arbitrary BS $m, m \in \boldsymbol{m}_s$.

The detailed algorithm is shown in Fig. 1. In step 1, algorithm initialization is established. BS set m' is the BSs participating in the algorithm execution. When m' is a null set, the algorithm is ended as step 3.4. The streams in set s'_m served by BS m will be changed when some streams in s'_m accomplish power allocation

```
Water-Filling with frequency diversity (WFFD)
Input:
    BSs set $\boldsymbol{m}$, $\boldsymbol{m}_s$, $\boldsymbol{s}_m$, $F_m^s$ for arbitrary $m$, $m \in \boldsymbol{m}$, and $s$, $s \in \boldsymbol{s}_m$, $P_{\max}$, $\widetilde{H}_{s_1,s_2}$ for arbitrary $s_1, s_2 \in \boldsymbol{s}_{\text{all}}$.
Output:
    $Q_s$ for arbitrary $s \in \boldsymbol{s}_{\text{all}}$.

1. Initialization:
  $p_m = P_{\max}$; $\boldsymbol{m}' = \boldsymbol{m}$; $\boldsymbol{s}'_m = \boldsymbol{s}_m$; Power of BS $m \in \boldsymbol{m}'$ pumped into stream $s \in \boldsymbol{s}'_m$, is initialized as $p_m^s = 0$;

2. WF power allocation based on the equivalent channel:
  for ($m$=1; $m \in \boldsymbol{m}'$; $m$++)
  {
    BS $m$ performs WF power allocation algorithm on the streams in $\boldsymbol{s}'_m$ with total power $p_m$, where the equivalent channel for stream $s \in \boldsymbol{s}'_m$ is $\widetilde{H}_{s,s}$.
    Thereafter, WF power allocation strategy $p'^s_m$ is obtained for stream $s$ served by BS $m$.
  }
3. Power adjustment:
  3.1) For (arbitrary BS $m$ in $\boldsymbol{m}'$)
      {
        3.1.1) Let $x_m^s = \frac{p'^s_m}{F_m^s}$, $\forall s \in s'_m$. BS $m$ transmit $x_m^s$ to BSs in the list $\boldsymbol{m}_s$, $s \in s'_m$.
        3.1.2) BS $m$ calculates $x_0^s = \min_{m \in \boldsymbol{m}_s} x_m^s$ for each $s \in \boldsymbol{s}'_m$. Thereafter, the overall power BS $m$ pumping into stream $s$ is determined by
               $p_m^s = p_m^s + F_m^s \times x_0^s$.
      }
  3.2) For (arbitrary BS $m$ in $\boldsymbol{m}'$)
      {
        Update $p_m = P_{\max} - \sum_{s \in s'_m} p_m^s$.
        If ($p_m = 0$)
        {
          For (arbitrary stream $s \in \boldsymbol{s}'_m$)
          {
            $\boldsymbol{s}'_{m'} = \boldsymbol{s}'_{m'}/\{s\}$, $\forall m' \in \boldsymbol{m}_s$
          }
        }
      }
  3.3) For (arbitrary BS $m$ in $\boldsymbol{m}'$)
      {
        If ($p_m = 0$, or $\boldsymbol{s}'_m$=null set)
        {
          $\boldsymbol{m}' = \boldsymbol{m}'/\{m\}$.
        }
      }
  3.4) If ($\boldsymbol{m}'$=null set) the algorithm is end, and $Q_s = \sum_{m \in \boldsymbol{m}_s} p_m^s$, $\forall s \in \boldsymbol{s}_{\text{all}}$ ; else go to step 2.
```

Fig. 1. Execution process of WFFD (WF with frequency diversity).

with condition in step 3.2. The available maximum power for each BS m is initialized as $p_m = P_{\max}$. On the other hand, the power of BS $m \in m'$ pumped into stream $s \in \boldsymbol{s}'_m$ is initialized as $p_m^s = 0$, where p_m^s will be accumulated in the circulations.

In step 2, arbitrary BS m in $\boldsymbol{m}'$ executes WF power allocation over all the streams in $\boldsymbol{s}'_m$ with total power p_m. As previously discussed, each stream is treated as a transmitter–receiver pair, where arbitrary $s \in s'_m$ goes through the equivalent channel $\widetilde{H}_{s,s}$. After WF, the power of arbitrary BS m in $\boldsymbol{m}'$ contributed to stream $s \in s'_m$ with p_m is denoted as p'^s_m.

The power on each stream is the accumulation of all BSs serving it. However, the power of arbitrary stream contributed by each BS may violate the power proportion determined by (17). In step 3.1.1, for arbitrary stream s, each BS m serving this stream calculates the unit power x_m^s with p'^s_m. In 3.1.2, we define the unit power of stream s as x_0^s, which is the minimum unit power in $\{x_m^s\}_{m \in \boldsymbol{m}_s}$. Based on x_0^s, each BS m serving s can adjust the power pumping into stream s as $p_m^s = p_m^s + F_m^s \times x_0^s$, where $F_m^s \times x_0^s$ is the power contributed by BS m to stream s in this circulation.

In step 3.2, each BS m in $\boldsymbol{m}'$ calculates and updates the total power p_m. If $p_m = 0$, arbitrary stream s in $\boldsymbol{s}'_m$ will be deleted from $\boldsymbol{s}'_{m'}$, where $m' \in \boldsymbol{m}_s$.

In step 3.3, arbitrary BS m with $p_m = 0$ will be deleted from $\boldsymbol{m}'$. Likewise, arbitrary BS m with an empty streams' list $\boldsymbol{s}'_m$ will be also deleted from $\boldsymbol{m}'$.

In step 3.4, if $\boldsymbol{m}'$ is updated to a null set, the algorithm is ended, or go to step 2 in circulation.

B. EPA-Based Power-Allocation Algorithm Description

In step 2 in Fig. 1, the WF-based algorithm can be directly acquired by an EPA with a frequency diversity-based algorithm (EPAFD), where each BS m in $\boldsymbol{m}'$ performs EPA power-allocation algorithm in the streams in $\boldsymbol{s}'_m$ with total power p_m, where the equivalent channel for stream $s \in \boldsymbol{s}'_m$ is $\widetilde{H}_{s,s}$.

As previously discussed, the stream analytical model proposed in Section III is an interesting and useful method for power allocation in a multiple-antenna system. In this section, we design a simple algorithm to execute WF and EPA power allocation in the MU-MIMO-based CoMP system via the stream model. Each stream plays as a transmit–receive pair and is also available to game with the initial power allocated by WFFD or EPAFD.

C. Discussion

The process of precoding contains two parts, i.e., the design of the precoder vectors at both the transmit end and the user end in Section III and executing power allocation in the directions of streams spanned by the precoder vectors. The design of precoding vectors and power allocation are two parts of the same process; the former forms the directions of transmit–receive vectors, and the latter determines the length of each vector. In this paper, for an arbitrary stream, the initial power allocation in Section IV is determined by the equivalent virtual channel gain defined in (19) and the power proportion per BS serving the stream in its CBS. Since the power allocation is limited by the power proportion determined by the directions of vectors and the BD precoder is designed to eliminate interference between streams after power allocation, the two parts are intrinsically integrated.

V. NONCOOPERATIVE PG MECHANISM WITH PRICING

With the power-allocation algorithm proposed in Section IV, WF or EPA initial power allocation is executed based on streams with the constraint of (24)–(26). However, the power strategy cannot be adapted to the varying wireless interference environment. On the other hand, WF algorithm does not take energy efficiency into consideration from the viewpoint of the system, which may lead to the degradation of both throughput and energy efficiency.

Although each BS tries to use the maximum power it initially allocates to the users to maximize the data rates, larger transmit power also leads to more serious interference and thus may decrease the total edge user throughput. Therefore, interference coordination is desired to maximize the overall throughput with appropriate power decreasing. Nash noncooperative game naturally lends itself to finding such a Nash power equilibrium point. Nash equilibrium (NE) [17], [18] is a solution of a noncooperative game involving all the players in the game. No player has incentive (denoted as best response function) to change its strategy for larger gain. Given the strategy spaces of players, if each player cannot gain further benefit, the strategy spaces constitute an NE. Noncooperative pricing game theorem can achieve a Nash power equilibrium point with less transmit power of BS to improve both user throughput and energy efficiency [1]. A key issue in a Nash noncooperative game is to prove whether the existence and uniqueness [17] of NE is guaranteed. Yates in [19] proposed a framework of interference function that provides a category of Nash noncooperative game catering for the existence and uniqueness of NE. Fu *et al.* further extend the framework to the CoMP scenario in [1]. Although noncooperative pricing game theorem is successfully applied to CoMP in [1], the goal to extend the approach to multiantenna CoMP with frequency diversity is difficult due to the matrix analysis based in (9). In this section, we easily achieve the goal by the stream analytical model proposed in Section III and the initial WFFD/EPAFD power-allocation algorithm in Section IV.

Nash Non-Cooperative Power Game

Input:

Transmission and scheduling result in each sub-band.

Output:

Power allocation strategy for each stream.

1. BD precoding:

With the transmission scheduling results, BD precoding is executed in each CBS coupled with the scheduled user set in it.

2. Stream analysis model:

By the transmit precoder matrix defined in Eq. (4) and receive precoder matrix in Eq. (6) of BD, each stream for a user is dealt with a transmit-receive pair.

3. Initial power allocation by WFFD/EPAFD:

From the point of stream, the system model is formulated as. (23)-(26). By the specific WFFD/EPAFD algorithm proposed in section IV, the initial power of each stream can be determined.

4. Nash Non-Cooperative Power Game

1) The initial power of each stream is taken as the power strategy space.

2) Each user can calculate the interference plus noise put on each stream of it in this circulation and feed back to its serving BS.

3) By (27), Streams in the same CBS update its transmit power in iteration with the interference plus noise. Each BS in the CBS contributes to the updated power of a stream according to the power proportion determined in (16).

4) When error between power regenerated by (27) and power in the last iteration of a stream is less than a small pre-determined threshold. The power game converges to its Nash equilibrium point.

Fig. 2. Execution process of Nash noncooperative PG.

For details, we give the initial power allocation and Nash noncooperative PG process in Fig. 2. In step 1, BD precoding is applied to each CBS in a centralized method while distributed operated between CBSs. In step 2, the stream analytical model is adopted in each CBS to set up a stream-based system. In step 3, we further apply the WFFD/EPAFD to determine the initial power in each stream. The algorithm is distributed between BSs to further lower the delay, which is important in CoMP. To achieve this, each BS applies WF/EPA algorithm to streams it serves. Thereafter, the power-allocation result of arbitrary BS will be sent to BSs in its CBS, based on which BSs can adjust the power to hold the power proportion proposed in (16). In step 4, each stream is dealt as a player in the game with power strategy space determined by WFFD/EPAFD and the game algorithm is distributed between streams.

Like in [1], the noncooperative game is featured by allowing different BSs to calculate the updated game power with the channel gain awareness as in (27), and thus, our algorithm is intelligent and environment adaptive. For an arbitrary stream s, assuming that its initial power is determined by WFFD or EPAFD as p^l_s, the virtual wireless channel power gain is denoted as $g_s + \tilde{H}_{s,s} \times (\tilde{H}_{s,s})^H$; then, the power of stream s can be updated as (27) in each iteration [1]

$$p_s = \frac{\left(1 - e^{-\left(\frac{g_s}{\beta}\right)}\right) \times z_s \times p_s^I}{z_s + e^{-\left(\frac{g_s}{\beta}\right)} \times p_s^I \times g_s} \tag{27}$$

TABLE I
SIMULATION PARAMETERS

Parameters	Values
BS power ($P_{\max}$)	46 dBm
Antenna gain per antenna (G)	5 dB
Fixed circuit power cost (C)	2dBm
System bandwidth (B)	20 MHz
Number of sub-band (S)	3
Cell radius (R)	0.5 Km
Number of antennas at BS (N_t)	4
Number of antennas at user (N_r)	2
Fast fading	Complex Gaussian distribution $\mathcal{CN}(0,1)$
Shadow model	log-normal distribution $\mathcal{N}(0, 8\text{ dB})$
Path loss model	$148.1 + 37.6\log_{10} d$
Noise power (σ^2)	-174 dBm/Hz
Number of cells ($\lvert \boldsymbol{m} \rvert$)	19
Frequency reuse factor	1
Number of users per cell (X)	100
Number of edge users per cell (U)	10
Maximum CBS size ($m_{\max}$)	3
Link	Down link

where β is the pricing factor, and Z_s is the interference plus noise of stream s. For $\beta \to 0$, we actually use no game, whereas as β increases, the game takes effect. The convergence of (27) has been proved in [1], which is omitted here for brevity. The specific pricing factor β maximizing the user throughput and energy efficiency can be empirically determined at the network planning stage, as discussed in Section VI.

The energy efficiency for this game approach is defined in (28) as

$$E = \frac{\Sigma_{s\in \boldsymbol{s}_{\text{all}}} r_s}{c \times |\boldsymbol{m}| + \Sigma_{s\in \boldsymbol{s}_{\text{all}}} p_s} \tag{28}$$

where $\sum_{s\in \boldsymbol{s}_{\text{all}}} r_s$ is the overall user throughput defined in (23), C is the fixed circuit power cost by each BS, and p_s is the power allocated to stream s.

VI. NUMERICAL RESULTS

A. Simulation Setup

Simulations are run in MATLAB 2010. The CoMP system consists of 19 cells with a frequency reuse factor of one. The number of subbands $S = 3$. The numbers of antennas configured by each BS and user are $N_t = 4$ and $N_r = 2$, respectively. Cell radius is set to 0.5 km, and $X = 100$ users are randomly scattered per cell. The channel energy values from associated BS are listed in a descending order, where the last $U = 10$ users are defined as edge users per cell. The fixed circuit power cost is 2 dBm. Table I gives the general simulation parameters. Unless otherwise specified, we set $B = 20$ MHz and $m_{\max} = 3$.

The schemes simulated in our work can be represented by either WFFD +game or EPAFD +game. The no game is denoted as NG, which corresponds to $\beta \to 0$ in (27), and thus can be taken as a special case of the case of game.

B. Impact of Pricing Factor β on the User Throughput

In Fig. 3, we give the simulation result showing the impact of pricing factor β on throughput and energy efficiency. In Fig. 3(a), $\beta = 0$ is corresponding to the NG case; when the number of subbands is one, it is the algorithm in [8]. As β increases, game takes effect. The increasing β promptly puts the throughput to the peak throughput at $\beta = 1.26 \times 10^{-13}$ for WFFD +game and $\beta = 1.78 \times 10^{-13}$ for EPAFD +game, respectively. Thereafter, the throughput gradually goes down. The WFFD-based game outperforms the EPAFD-based one since WFFD more effectively adapts to the wireless environment than EPAFD. In Fig. 3(b), energy efficiency for both WFFD- and EPAFD-based algorithms rises; since more power is cut down than the counterpart in throughput, the EPAFD-based algorithms outperform WFFD-based ones. EPAFD may be more effective in power reduction than WFFD due to the environment-adaptive feature in (27), where streams with poor channel gain will consume more power via game. In Fig. 3(c) and (d), the user throughput and energy efficiency of the algorithm in [1] are demonstrated, respectively. It is shown that our algorithms proposed in this paper outperform the algorithm in [1] because the algorithm in [1] is corresponding to the single-antenna without precoding scenario, which largely limits the CoMP performance.

C. Impact of Different Scenarios on the User Throughput

In this section, we focus on the impact of different scenarios on user throughput and energy efficiency. In Fig. 4, the effects of power-allocation gain (PAG) on user throughput [see Fig. 4(a)–(d)] and energy efficiency [see Fig. 4(e)–(h)] with specific configuration of cell radius, the number of edge users U, the maximum CBS size $m_{\max}$, and the pricing factor are studied sequentially.

In Fig. 4(a) and (e), a large cell radius is assumed. It is observed that the throughput is deteriorated due to the weakened intended signal. In this scenario, each BS needs a large transit power to keep the receive SINR at user end. If the power is cut down by a pricing factor, user throughput will decrease, which leads to a less energy efficiency gain in Fig. 4(e) than that in Fig. 3(b).

In Fig. 4(b) and (f), the number of edge users is promoted to $U = 30$, based on which the edge users selected will enjoy better wireless channel quality. The throughput and energy efficiency will rise with β increased. The algorithm performance is enhanced than that in Fig. 3.

In Fig. 4(c) and (g), the number of maximum CBS size $m_{\max}$ is reconfigured as $m_{\max} = 5$, where more BSs can be classified into a CBS. We observe that the throughput gain is less than that in Fig. 3(a) since some inferior wireless channels are contained in a CBS. However, the energy efficiency in Fig. 4(g) outperforms that in Fig. 3(b) since the improper coordination relationship in a CBS will lead to larger power deduction via the adjustment of wireless channel gain g_s for each stream s in (27).

As observed above, energy efficiency always increases in each scenario. To find a more exact relationship between energy efficiency and pricing factor β, we enlarge β in Fig. 4(d) and (h). Because of excessive power deduction by pricing punishment, user throughput in Fig. 4(d) sharply

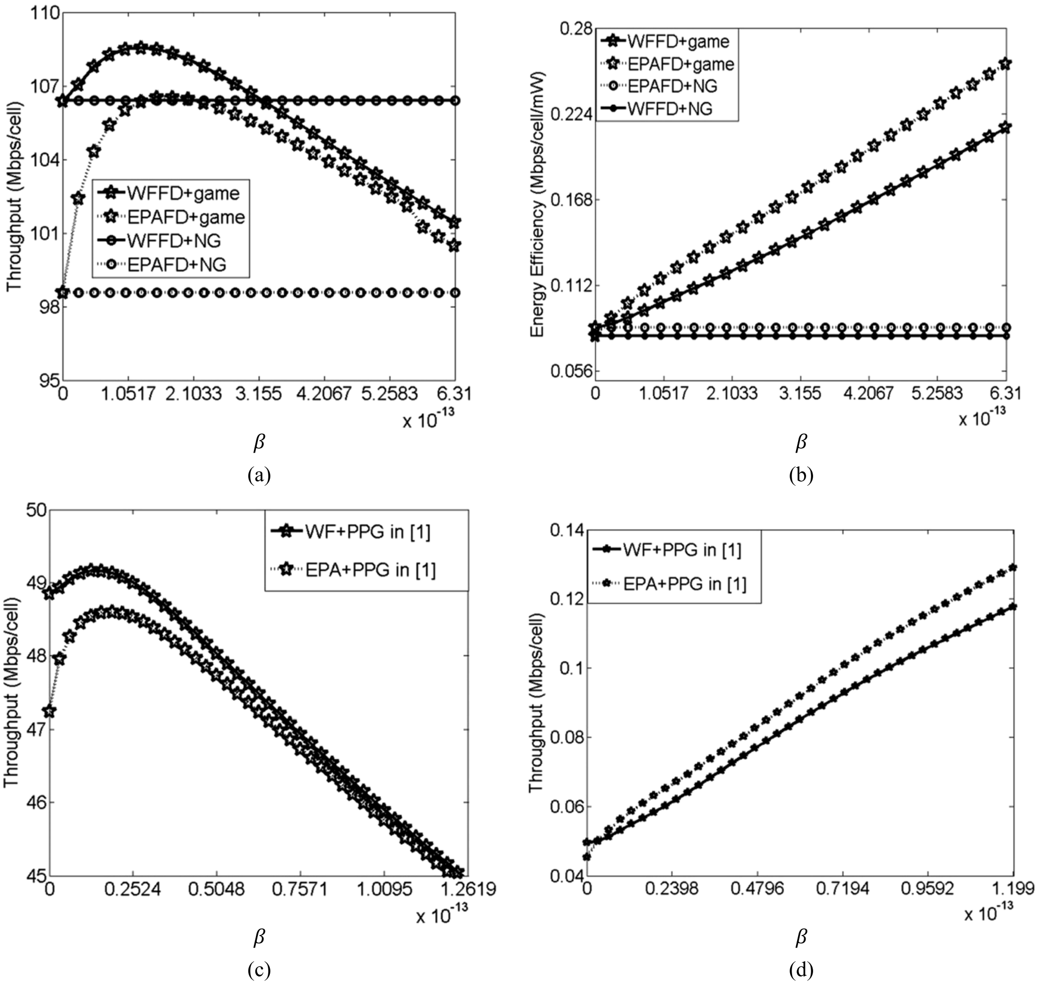


Fig. 3. Impact of pricing factor β. (a) Throughput–β. (b) Energy efficiency–β. (c) Throughput–β in [1]. (d) Energy efficiency–β in [1].

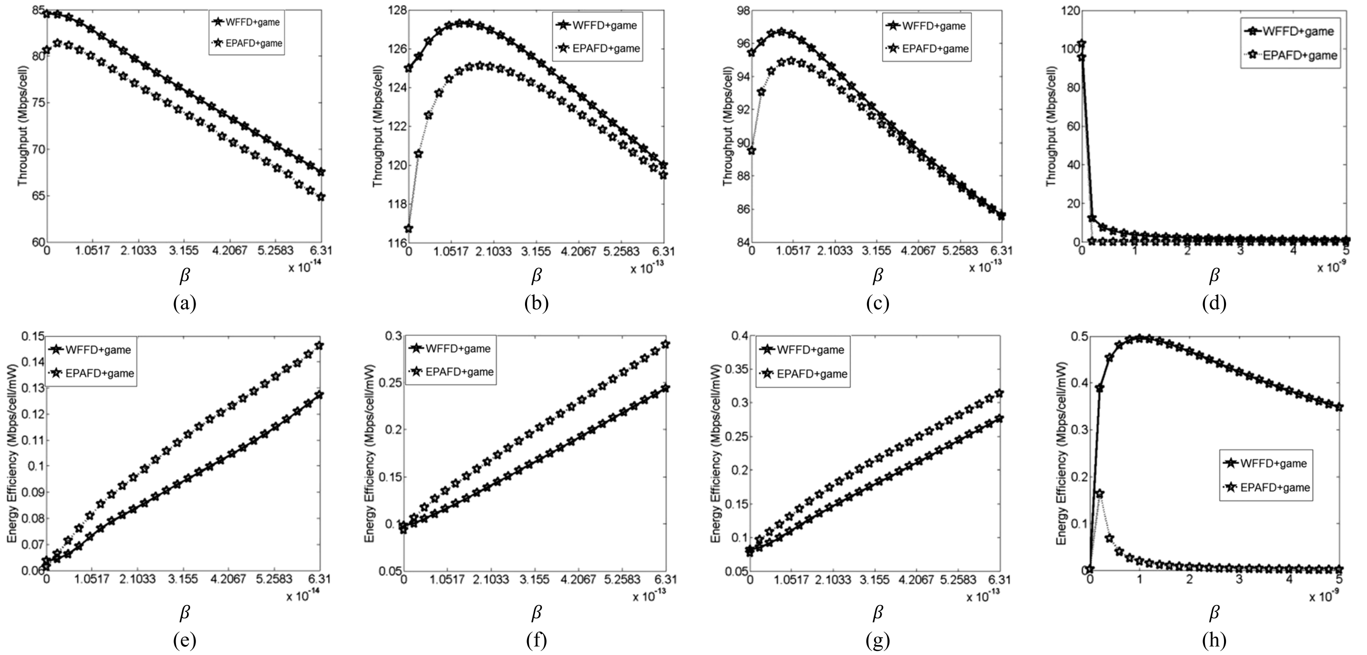
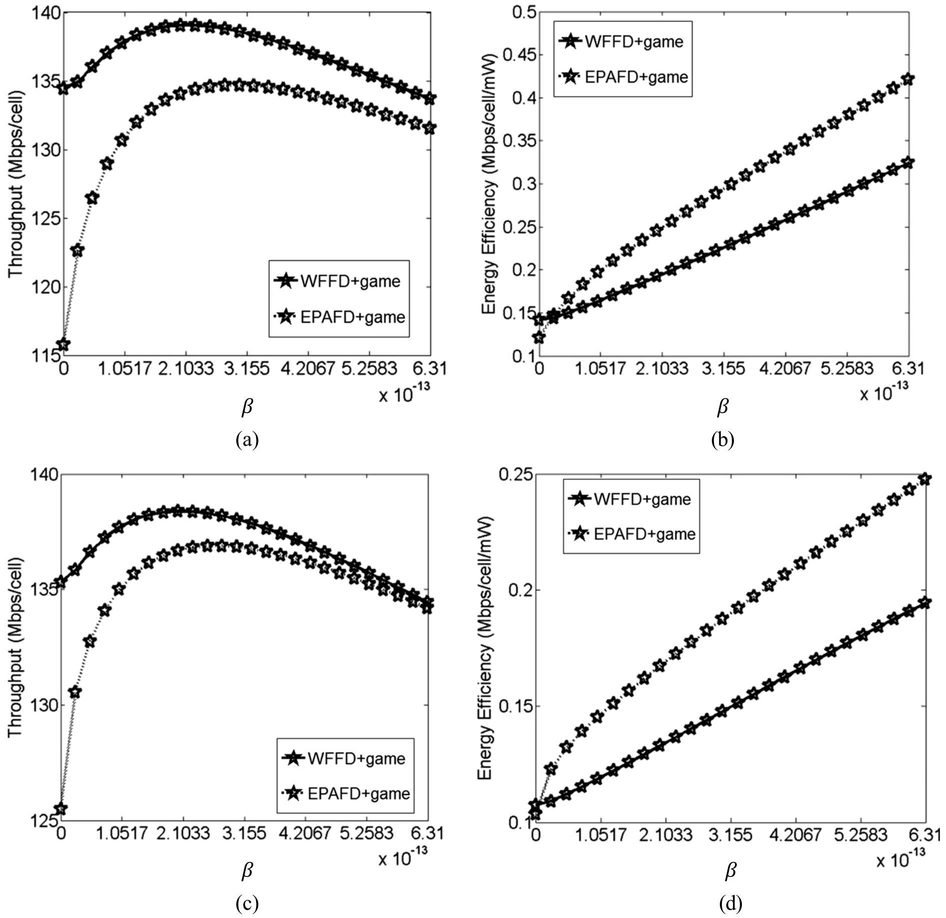


Fig. 4. Impact of different system parameter configurations on both user throughput and energy efficiency. (a) Throughput–β ($R = 1.5$ km). (b) Throughput–β ($U = 30$). (c) Throughput–β ($m_{\max} = 5$). (d) Throughput–β (large pricing factor). (e) Energy efficiency–β ($R = 1.5$ km). (f) Energy efficiency–β ($U = 30$). (g) Energy efficiency–β ($m_{\max} = 5$). (h) Energy efficiency–β (large pricing factor).



(a) (b)

(c) (d)

Fig. 5. Impact of N_t and N_r on both user throughput and energy efficiency. (a) Throughput–β $(N_t = 24)$. (b) Energy efficiency–β $(N_t = 24)$. (c) Throughput–β $(N_r = 4)$. (d) Energy efficiency–β $(N_r = 4)$.

shrinks. In Fig. 4(h), we find that the energy efficiency gradually achieves its peak value and then drops for both WFFD +game and EPAFD +game as β increases. This drop can be explained as follows. The excessive power deduction will lead to a very low throughput, where the impact of throughput largely surpasses that of power on energy efficiency. On the other hand, energy efficiency of WFFD +game in Fig. 4(h) outperforms it in EPAFD +game. The reason is that the initial power via WFFD +game is more reasonable than that via EPAFD +game and more power can be retained to improve the user throughput.

D. Impact of N_t and N_r on the User Throughput

In Section VI-C, we focus on the impact of some system parameters on the throughput and energy efficiency and provide more in-depth discussions.

In Fig. 5(a) and (b), we give the PAG performance with reconfigured N_t and N_r, respectively. In Fig. 5(a) and (b), $N_t = 24$ are assumed, whereas in Fig. 5(c) and (d), $N_r = 4$ are assumed.

As observed in Fig. 5(a) and (c), either increasing N_t or N_r can largely improve user throughput. The difference is that adding N_t at the transmit end supports user throughput improvement via improving the virtual equivalent channel defined in (19), whereas adding N_r at the receive end supports user throughput improvement via increasing the number of streams. By comparison, the effects of adding N_r are more notably than those of adding N_t at the transmit end. This suggests that adding N_r is more cost efficient than adding N_t. However, it is difficult for receive users to be equipped with a large number of N_r at from the perspective of engineering practice. On the other hand, energy efficiency in Fig. 5(b) is higher than that in Fig. 3(b). The reason is that the improved virtual equivalent channel enhances the effects of PAG, where the same power pricing can support a larger user throughput than the throughput in Fig. 3(b). The energy efficiency in Fig. 5(d) does not significantly change compared with that in Fig. 3(b) since adding streams in CoMP cannot improve the virtual equivalent channel gain.

VII. CONCLUSION

In this paper, a framework of noncooperative Nash PG with pricing applied to downlink multiantenna-based CoMP with frequency diversity has been proposed for frequency-selective channels. This approach improves the system throughput by three independent steps

1) A stream analytical model has been established to decompose the complicated matrix analysis-based system model into multiple single-antenna transmit–receive pairs with some practical constraints in CoMP.
2) We have proposed a distributed WF/EPA-based power-allocation algorithm with frequency diversity in CoMP.
3) A framework of noncooperative PG has been used to further enhance user throughput and energy efficiency.

In particular, we reformulate BD precoding-based multiple-antenna CoMP as stream-based multiple single-antenna transmitter–receiver pairs' system. Thereafter, WFFD/EPAFD +game power-allocation algorithm dedicated to multiple-antenna CoMP with frequency diversity is executed by BSs in a distributed manner. Based on the WFFD/EPAFD +game result, strategy space in the PG for each stream is determined and the user throughput and energy efficiency are further improved by the game. We have demonstrated the superior performance of the proposed framework via in-depth discussions and extensive simulations.

REFERENCES

[1] S. Fu, B. Wu, H. Wen, and G. Feng, "Transmission scheduling and game theoretical power allocation for interference coordination in CoMP," *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 112–123, Jan. 2014.

[2] A. Papadogiannis, D. Gesbert, and E. Hardouin, "A dynamic clustering approach in wireless networks with multi-cell cooperative processing," in *Proc. IEEE ICC*, 2008, pp. 4033–4037.

[3] E. Pateromichelakis, M. Shariat, A. Quddus, and R. Tafazolli, "On the evolution of multi-cell scheduling in 3GPP LTE/LTE-A," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 2, pp. 701–717, 2nd Quart. 2013.

[4] P. Marsch, M. Grieger, and G. Fettweis, "Field trial results on different uplink coordinated multi-point (CoMP) concepts in cellular systems," in *Proc. IEEE GLOBECOM*, 2010, pp. 1–6.

[5] H. Zhang, H. Zhang, H. Liu, C. Jiang, and X. Chu, "A practical semi-dynamic clustering scheme using affinity propagation in cooperative picocells," *IEEE Trans. Veh. Technol.*, vol. 64, no. 9, pp. 4372–4377, 2015.

[6] A. Papadogiannis, H. J. Bang, D. Gesbert, and E. Hardouin, "Efficient selective feedback design for multicell cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 60, no. 1, pp. 196–205, Jan. 2011.

[7] J. G. Andrews, S. Buzzi, W. Choi, and S. V. Hanly, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[8] J. Zhang, R. Chen, J. G. Andrews, A. Ghosh, and R. W. Heath, "Networked MIMO with clustered linear precoding," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1910–1921, Apr. 2009.

[9] P. Marsch, M. Grieger, and G. Fettweis, "Large scale field trial results on different uplink coordinated multi-point (CoMP) concepts in an urban environment," in *Proc. IEEE WCNC*, Mar. 2011, pp. 1858–1863.

[10] G. Fodor, M. Johansson, and P. Soldati, "Near optimum power control under fairness constraints in CoMP systems," in *Proc. IEEE GLOBECOM* 2009, pp. 1–8.

[11] F. Meshkati, M. Chiang, H. V. Poor, and S. C. Schwartz "A game-theoretic approach to energy-efficient power control in multicarrier CDMA systems," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 6, pp. 1115–1129, Jun. 2006.

[12] G. Miao, N. Himayat, G. Li, and S. Talwar, "Distributed interference aware energy-efficient power optimization," *IEEE Trans. Wireless Commun.*, vol. 10, no. 4, pp. 1323–1333, Apr. 2011.

[13] D. Qiao, M. C. Gursoy, and S. Velipasalar, "The impact of QoS constraints on the energy efficiency of fixed-rate wireless transmissions," *IEEE Trans. Wireless Commun.*, vol. 8, no. 12, pp. 5957–5969, Dec. 2009.

[14] K. W. Shum, K. K. Leung, and C. W. Sung, "Convergence of iterative waterfilling algorithm for Gaussian interference channels," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 6, pp. 1091–1100, Aug. 2007.

[15] Y. Noam and A. Leshem, "Iterative power pricing for distributed spectral coordination in DSL networks," *IEEE Trans. Commun.*, vol. 57, no. 4, pp. 948–953, Apr. 2009

[16] D. H. N. Nguyen, H. N. Le, and T. Le-Ngoc, "Block-diagonalization precoding in a multiuser multicell MIMO system: Competition and coordination," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 968–981, Feb. 2014.

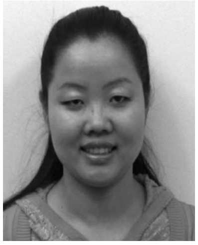
[17] T. Roughgarden, T. Tardos, and V. V. Vazirani, *Algorithmic Game Theory*. Cambridge, U.K.: Cambridge Univ. Press, 2007.

[18] Z. Han, D. Niyato, W. Saad, T. Basar, and A. Hjrungnes,*Game Theory in Wireless and Communication Networks: Theory, Models and Applications*. Cambridge, U.K.: Cambridge Univ. Press, 2011.

[19] R. Yates, "A framework for uplink power control in cellular radio system," *IEEE J. Sel. Areas Commun.*, vol. 13, no. 7, pp. 1341–1347, Sep. 1995.

Shu Fu received the B.Eng. and M.Eng. degrees in telecommunication engineering from Chongqing University of Posts and Telecommunications, Chongqing, China, in 2007 and 2012, respectively. He is currently working toward the Ph.D. degree in the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, Chengdu, China, and since 2014, he has been a joint Ph.D. Student at the University of Waterloo, Waterloo, ON, Canada.

His research interests include wireless communication, data center networks, and optical wireless integration networks.



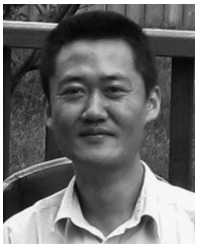
Hong Wen received the M.Sc. degree in electrical engineering from Sichuan University, Chengdu, China, in 1997 and the Ph.D. degree from Southwest Jiaotong University, Chengdu, in 2014.

Then, she became an Associate Professor with the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China (UESTC), Chengdu. From January 2008 to August 2009, she was a Visiting Scholar and a Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. She is currently a Professor with the UESTC. Her major interests focus on wireless communication systems.

Jinsong Wu (SM'11) received PhD in electrical and computer engineering from Queen's University, Kingston, Canada.

He currently works as Associate Professor in the Department of Electrical Engineering, Universidad de Chile, Santiago, Chile. He is the coauthor and leading editor of the comprehensive book titled "Green Communications: Theoretical Fundamentals, Algorithms, and Applications" (CRC Press, September 2012).

Mr. Wu is the Founder and Founding Chair of the Technical Committee on Green Communications and Computing (TCGCC), IEEE Communications Society, which was established in 2011 as an official technical subcommittee and elevated as TCGCC in 2013. He is the Founder and Series Editor on *Green Communication and Computing Networks* of the IEEE COMMUNICATIONS MAGAZINE. He has been a Guest Editor of the IEEE SYSTEMS JOURNAL, the IEEE ACCESS journal, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, and Elsevier's *Computer Networks*. He is an Associate Editor of IEEE COMMUNICATIONS SURVEYS & TUTORIALS, the IEEE SYSTEMS JOURNAL, and IEEE ACCESS and an Editor of KSII Transactions on Internet and Information Systems and the IEEE COMMUNICATIONS MAGAZINE.



Bin Wu (S'04–M'07) received the Ph.D. degree in electrical and electronic engineering from The University of Hong Kong, Pokfulam, Hong Kong, in 2007.

From 2007 to 2012, he was a Postdoctoral Research Fellow with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. He is currently a Professor with the School of Computer Science and Technology, Tianjin University, Tianjin, China. His research interests include computer systems and networking and communication system design.

View publication stats