Joint Preprocessing Techniques for Downlink CoMP Transmission in Multipath Fading Channels

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Abstract*—An elaborate coordination among multiple cells called coordinated multipoint (CoMP) transmission/reception is adopted by LTE-A to improve coverage and cell-edge throughput. This paper derives various joint precoding techniques among coordinated cell sites to address the serious co-channel interference (CCI) for downlink CoMP broadband transmission. They include joint time-division multiple access (J-TDMA), joint zero-forcing (J-ZF), joint minimum mean square error (J-MMSE), and joint null-space decomposition (J-NSD). The J-TDMA scheme is automatically free from CCI at the cost of sacrificing spectral efficiency. The J-ZF scheme enables complete suppression of interference, but is at the expense of demanding higher transmitter power on precoding process. The performance of J-MMSE is close to the J-TDMA since it makes a good tradeoff between interference suppression and transmitter power efficiency. In J-NSD, the CCI is completely removed but it comes with a penalty in that a user's transmission is constrained to a smaller subspace. The precoding is done under the perfect channel state information and thus the simulation results in this paper provide an upper-bound reference for these precoding schemes.

Keywords- CoMP, joint preprocessing, precoding, OFDM

I. INTRODUCTION

The demands for high date rate and high spectral efficiency are ever growing at an extremely rapid pace for wireless communication services. However, the radio resources are often scarce. Therefore, the spectrally efficient communication is a major design goal for next-generation (4G) wireless communication systems. Both Long-Term Evolution Advanced (LTE-A) and Worldwide Interoperability for Microwave Access (WiMAX) adopt orthogonal frequency-division multiplexing (OFDM) as their multiple access schemes. OFDM is an effective technique to avoid the serious inter-symbol interference (ISI) in high-data rate transmissions and to improve the spectral efficiency by overlapping the orthogonal sub-carriers.

To obtain best use of the valuable spectrum, 4G cellular systems like LTE-A and WiMAX are designed to support universal frequency reuse (UFR). However, actual implementations of UFR in cellular wireless networks lead to unacceptable interference levels experienced by users near the cell-edge area. To this end, interference management has been considered as one of the major issues currently being investigated by different 4G standardization bodies and forums.

Inter-cell interference coordination (ICIC) is one of the key techniques to mitigate the inter-cell interference (ICI) [1]. The ICIC approach capitalizes on efficient radio resource management (RRM) techniques to coordinate the channel allocation in nearby cells so as to minimize the interference level. In addition, an elaborate coordination among multiple cells called coordinated multipoint (CoMP) transmission/reception is adopted as a key technique for LTE-A to improve coverage and cell-edge throughput [2]. The main idea of CoMP is as follows: cell-edge users may be able to receive signals from multiple cell sites and the users' transmission may be received at multiple cell sites. Based on this fact, the downlink/uplink (DL/UL) performance can be increased significantly, if the signal transmissions from multiple cell sites/cell-edge users are coordinated.

For the CoMP transmission, there exist two major techniques. One is the scheduling/beamforming (CS/CB) and another is the joint processing/transmission (JP/JT) [3-5]. In the CS/CB technique, the transmission to a certain user comes from its serving cell, exactly as in the case of traditional point-to-point transmission. However, the CS/CB transmission is coordinated among multiple coordinated cells in order to control and/or reduce the unnecessary interference to other transmissions scheduled within the coordinated cells. In the JP/JT approach, multiple adjacent base stations (BSs) simultaneously transmit to a given set of cell-edge users through spatial precoding process. The multipoint transmissions will be coordinated as a single transmitter with antennas that are geographically separated. The JP/JT approach achieves higher performance, as compared with coordination only in the scheduling, but it comes at the expense of more stringent requirement on backhaul communication [6].

With BS cooperation, the information-theoretic capacity has been studied in various scenarios for *narrowband* wireless systems [7-9]. In [7], BS cooperation approach is proposed to enhance the DL sum capacity with single-input single-output (SISO) systems employed in each cell, by implementing optimum dirty paper coding (DPC) [10]. In [8], some more practical joint transmission schemes are studied for DL multi-user MIMO communications with cooperative multi-cell BSs. The authors in [9] explore coherently coordinated transmission from multiple BSs to each user. In this paper, we aim to derive various joint precoding schemes among multiple coordinated BSs and evaluate their bit error rate (BER) performance for DL CoMP broadband

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transmission with orthogonal-frequency multiple-access (OFDMA). We assume that the precoding is done under the perfect channel state information (CSI) among coordinated BSs. However, the performance of the multi-cell MIMO is limited by coarse quantization (using codebook) [6]. Thus the performance in this paper provides an upper-bound reference for these precoding schemes. The rest of the paper is organized as follows. The system model is described in Section 2. In Section 3, JP/JT techniques for the DL CoMP broadband transmission are presented. Simulation results are given in Section 4. Finally, conclusions are given in Section 5.

II. SYSTEM MODEL

Consider the LTE-A DL CoMP broadband transmission which adopts OFDMA as its multiple-access scheme. An example of DL CoMP scenario is depicted in Fig. 1, where three BSs coordinate to create a multipoint transmission to multiple cell-edge users. Assume there exist N_b cooperative BSs to serve N_u co-channel cell-edge users in which each BS and each user are equipped with N_t and N_r transmit and receive antennas, respectively. The N-point inverse discrete Fourier transform (IDFT) sequence sent for cell-edge user u from the qth transmit antenna of BS b is given by

$$x_n^{(b,u,q)} = \frac{1}{N}\sum_{k\in\Im_{(u)}} X_k^{(b,u,q)} \exp\left(j\frac{2\pi kn}{N}\right), 0 \le n \le N-1 \quad (1)$$

where $\Im_{(u)}$ denotes the set of indices for the sub-carriers of a sub-channel allocated to user u and $X_k^{(b,u,q)}$ represents the transmitted symbol over sub-carrier k. A proper length of cyclic prefix is appended to the sequence such that there is no inter-OFDM symbol interference.

Then the signal received by the user u at the receive antenna v from the N_b coordinated BSs is

$$\begin{aligned} y_n^{(u,v)} = & \sum_{b=0}^{N_b-1}\sqrt{K^{(b,u)}}\Bigg\{\sum_{q=0}^{N_t-1}\sum_{l=0}^{L_{(b,u)}-1} h_l^{(b,u,q,v)} x_{(n-\tau_{(b,u)}-l)_N}^{(b,u,q)} + \\ & \sum_{\substack{u'=0\\(u'\neq u)}}^{N_u-1}\sum_{q=0}^{N_t-1}\sum_{l=0}^{L_{(b,u)}-1} h_l^{(b,u,q,v)} x_{(n-\tau_{(b,u)}-l)_N}^{(b,u',q)}\Bigg\} + \\ & w_n^{(u,v)}, \qquad 0\le n\le N-1 \end{aligned} \quad (2)$$

where $K^{(b,u)}$ is the propagation loss due to path loss, the set of samples $\left\{w_n^{(u,v)}\right\}$ denotes the received white Gaussian noise samples and $(k)_N$ denotes the operation of k modulo N. The set of $L_{(b,u)}$ multipath coefficients $\left\{h_l^{(b,u,q,v)}\right\}$ denotes the channel impulse response (CIR) between transmit antenna q and receive antenna v from BS b to user u and are modeled as zero-mean, uncorrelated, complex Gaussian variables. The path loss coefficient is modeled as $K^{(b,u)} = \beta_0 d_{(b,u)}^{-\gamma}$, where β_0 is a propagation constant, $d_{(b,u)}$ is the propagation distance, and γ the path loss exponent [11]. Assume that the effective maximum delay spread among all the cooperative BSs to each user u is within the tolerance of cyclic-prefix. Thus there is no inter-OFDM symbol interference.

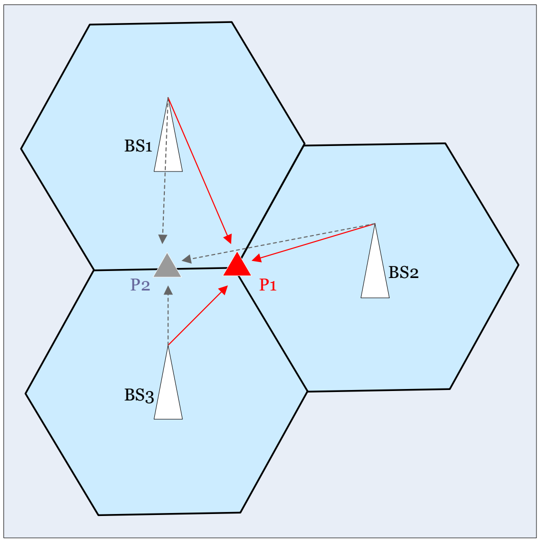

Fig. 1 A CoMP framework for DL transmission

After taking discrete Fourier transform (DFT), the DFT samples received at the antenna v of user u are given by

$$\begin{aligned} Y_k^{(u,v)} = & \sum_{b=0}^{N_b-1}\sqrt{K^{(b,u)}}\Bigg\{\sum_{q=0}^{N_t-1}\lambda_k^{(b,u,q,v)} X_k^{(b,u,q)} + \\ & \sum_{\substack{u'=0\\(u'\neq u)}}^{N_u-1}\sum_{q=0}^{N_t-1}\lambda_k^{(b,u,q,v)} X_k^{(b,u',q)}\Bigg\} + W_k^{(u,v)}, \quad k\in\Im_{(u)} \end{aligned} \quad (3)$$

where $\lambda_k^{(b,u,q,v)} \equiv \sum_{l=0}^{L_{(b,u)}-1} h_l^{(b,u,q,v)} e^{j2\pi k(\tau_{(b,u)}+l)/N}$ denotes the channel gain over sub-carrier k from transmit antenna q of BS b to receive antenna v of user u. The additive white Gaussian noise (AWGN) with single-sided power spectral density N_0 at sub-carrier k is represented by $W_k^{(u,v)}$, which is obtained from the DFT of the noise samples $\left\{w_n^{(u,v)}\right\}$. Let the set of indices $\left\{I_k^{(u)}, k = 0,1,\cdots,\left|\Im_{(u)}\right|-1\right\}$ be the sub-carrier indices in $\Im_{(u)}$, where the cardinality of the set $\Im_{(u)}$ is denoted by $\left|\Im_{(u)}\right|$. With (3), we define the $\left|\Im_{(u)}\right|\times 1$ received signal vector $\mathbf{Y}^{(u,v)}$, whose kth element is $Y_{I_k^{(u)}}^{(u,v)}$.

Let $\mathbf{\Lambda}^{(b,u,v)} \equiv \left[\mathbf{\Lambda}^{(b,u,0,v)},\cdots,\mathbf{\Lambda}^{(b,u,N_t-1,v)}\right]$, which denotes the $\left|\Im_{(u)}\right|\times\left|\Im_{(u)}\right|N_t$ aggregate channel matrix observed at receive antenna v of user u from BS b. Similarly, the aggregate channel matrix observed at the antenna v of user u from all N_b BSs is $\mathbf{\Lambda}^{(u,v)} \equiv \left[\mathbf{\Lambda}^{(0,u,v)},\cdots,\mathbf{\Lambda}^{(N_b-1,u,v)}\right]$. The signals sent to user u from N_t transmit antennas of BS b can be represented as the $\left|\Im_{(u)}\right|N_t\times 1$ aggregate signal vector $\mathbf{X}^{(b,u)} \equiv \left[\mathbf{X}^{(b,u,0)^T},\cdots,\mathbf{X}^{(b,u,N_t-1)^T}\right]^T$, where $\mathbf{X}^{(b,u,q)}$ is $\left|\Im_{(u)}\right|\times 1$ vector whose kth entry is $X_{I_k^{(u)}}^{(b,u,q)}$. In order to have an insight into the coordinated transmission among BSs, we cascade all the $\left|\Im_{(u)}\right|\times 1$ received vectors at all N_r receive antennas to form a single $\left|\Im_{(u)}\right|N_r\times 1$ received vector as follows.

$$\mathbf{Y}^{(u)} \equiv \left[\mathbf{Y}^{(u,0)^T}, \mathbf{Y}^{(u,1)^T}, \cdots, \mathbf{Y}^{(u,N_r-1)^T}\right]^T = \boldsymbol{\Lambda}^{(u)}\left(\mathbf{X}^{(u)} + \sum_{\substack{u'=0 \\ (u'\neq u)}}^{N_u-1} \mathbf{X}^{(u')}\right) + \mathbf{W}^{(u)}, \tag{4}$$

where $\boldsymbol{\Lambda}^{(u)} \equiv \left[\boldsymbol{\Lambda}^{(u,0)^T}, \cdots, \boldsymbol{\Lambda}^{(u,N_r-1)^T}\right]^T$ denotes the $|\mathfrak{I}_{(u)}|N_r \times |\mathfrak{I}_{(u)}|N_b N_t$ aggregate channel matrix of user u, $\mathbf{X}^{(u)} \equiv \left[\mathbf{X}^{(0,u)^T}, \cdots, \mathbf{X}^{(N_b-1,u)^T}\right]^T$ is the $|\mathfrak{I}_{(u)}|N_b N_t \times 1$ aggregate signal vector sent for user u from all N_b coordinated BSs, and $\mathbf{W}^{(u)}$ is the $|\mathfrak{I}_{(u)}|N_r \times 1$ aggregate received noise vector. The N_b cooperative BSs jointly design a $|\mathfrak{I}_{(u)}|N_b N_t \times K_{(u)}$ preprocessing matrix $\mathbf{F}^{(u)}$ to generate the aggregate signal vector $\mathbf{X}^{(u)}$ in order to mitigate co-channel interference (CCI) from the other $N_u - 1$ co-channel users. That is, the coordinated BSs cooperate to send a $K_{(u)} \times 1$ data vector $\mathbf{d}^{(u)} \equiv \left[d_0^{(u)}, \cdots, d_{K_{(u)}-1}^{(u)}\right]^T$ to user u through the preprocessing matrix $\mathbf{F}^{(u)}$ resulting in the following transmit signal vector.

$$\mathbf{X}^{(u)} = \mathbf{F}^{(u)}\mathbf{d}^{(u)}, \qquad u = 0,1,\cdots,N_u - 1. \tag{5}$$

Let $K \equiv \sum_{u=0}^{N_u-1} K_{(u)}$. Substituting (5) into (4) yields the following:

$$\mathbf{Y}^{(u)} = \boldsymbol{\Lambda}^{(u)}\mathbf{F}\mathbf{d} + \mathbf{W}^{(u)}, \qquad u = 0,1,\cdots,N_u - 1 \tag{6}$$

where $\mathbf{d} \equiv \left[\mathbf{d}^{(0)^T}, \cdots, \mathbf{d}^{(N_u-1)^T}\right]^T$ is the $K \times 1$ aggregate data vector and $\mathbf{F} \equiv \left[\mathbf{F}^{(0)}, \cdots, \mathbf{F}^{(N_u-1)}\right]$ is the $|\mathfrak{I}_{(u)}|N_b N_t \times K$ aggregate preprocessing matrix.

III. Joint Preprocessing Techniques for Downlink CoMP Broadband Transmission

Several joint preprocessing transmission techniques with per BS power constraint are derived to effectively eliminate the CCI appearing at the user side. They include joint time-division multiple access (J-TDMA), joint zero-forcing (J-ZF), joint minimum mean-square error (J-MMSE), and joint null-space decomposition (J-NSD). In J-TDMA transmission scheme, the coordinated BSs simultaneously serve only one cell-edge user at each time slot. At the cost of sacrificing spectral efficiency, the J-TDMA scheme is automatically free from CCI. Thus the J-TDMA scheme will be served as a benchmark for the BER performance.

The joint design of $\mathbf{F}$ is subject to the per BS power constraint P_t. According to (5), the preprocessing matrix for user u is decomposed as $\mathbf{F}^{(u)} \equiv \left[\mathbf{F}^{(0,u)^T}, \cdots, \mathbf{F}^{(N_b-1,u)^T}\right]^T$, where the sub-matrix $\mathbf{F}^{(b,u)} \in \mathbb{C}^{|\mathfrak{I}_{(u)}|N_t \times K_{(u)}}$ is used by BS b to pre-process the data vector $\mathbf{d}^{(u)}$ sent to user u. That is, $\mathbf{X}^{(b,u)} = \mathbf{F}^{(b,u)}\mathbf{d}^{(u)}$.

A. J-TDMA transmission scheme

By singular value decomposition (SVD), for cell-edge user u its $|\mathfrak{I}_{(u)}|N_r \times |\mathfrak{I}_{(u)}|N_b N_t$ aggregate channel matrix $\boldsymbol{\Lambda}^{(u)}$ can be decomposed as $\boldsymbol{\Lambda}^{(u)} = \mathbf{U}^{(u)}\mathbf{D}^{(u)}\left(\mathbf{V}^{(u)}\right)^H$, where $\mathbf{D}^{(u)}$ is the diagonal matrix with singular values and $\mathbf{U}^{(u)}$ and $\mathbf{V}^{(u)}$ are unitary matrices with left and right singular column vectors, respectively. Recall that the number of data symbols sent to user u during each time of cooperative transmission is $K_{(u)}$, which will equal the number of non-zero singular values (also equal the rank of $\boldsymbol{\Lambda}^{(u)}$). The non-zero singular values $\left\{\sigma_k^{(u)}\right\}$ appear on the first $K_{(u)}$ diagonal entries of $\mathbf{D}^{(u)}$, which form the $K_{(u)} \times K_{(u)}$ diagonal matrix $\boldsymbol{\Sigma}^{(u)}$.

To serve user u, the aggregate preprocessing matrix becomes $\mathbf{F} = \left[\mathbf{0}, \cdots, \mathbf{0}, \mathbf{F}^{(u)}, \mathbf{0}, \cdots, \mathbf{0}\right]$, where $\mathbf{F}^{(u')} = \mathbf{0}$ for $u' \neq u$. The columns of $\mathbf{F}^{(u)}$ is composed of the first $K_{(u)}$ right singular columns in $\mathbf{V}^{(u)}$. Then the $|\mathfrak{I}_{(u)}|N_r \times 1$ received vector at user u in (6) can be rewritten as

$$\mathbf{Y}^{(u)} = \mathbf{U}^{(u)}\begin{bmatrix}\boldsymbol{\Sigma}^{(u)} \\ \mathbf{0}\end{bmatrix}\mathbf{d}^{(u)} + \mathbf{W}^{(u)}. \tag{7}$$

Transforming the received vector $\mathbf{Y}^{(u)}$ by the unitary matrix $\mathbf{U}^{(u)^H}$ $\left(\text{i.e.}, \tilde{\mathbf{Y}}^{(u)} = \mathbf{U}^{(u)^H}\mathbf{Y}^{(u)}\right)$ results in the following $K_{(u)}$ equivalent parallel channels:

$$\tilde{Y}_k^{(u)} = \sigma_k^{(u)}\sqrt{P_k^{(u)}}d_k^{(u)} + W_k^{(u)}, \quad k = 0,1,\cdots,K_{(u)} - 1, \tag{8}$$

where $\tilde{Y}_k^{(u)}$ is the kth element of $\tilde{\mathbf{Y}}^{(u)}$, $P_k^{(u)}$ denotes the transmit power of $d_k^{(u)}$ and the kth entry of $\mathbf{U}^{(u)^H}\mathbf{W}^{(u)}$ is $W_k^{(u)}$, which follows the same distribution as the noise samples in $\mathbf{W}^{(u)}$.

B. J-ZF preprocessing scheme

The J-ZF scheme intends to completely remove the multiuser interference from the received signal by jointly pre-coding the aggregate data vector $\mathbf{d}$ at multiple cooperative BSs. Stacking up the N_u received vectors in (6) yields

$$\mathbf{Y} \equiv \left[\mathbf{Y}^{(0)^T}, \mathbf{Y}^{(1)^T}, \cdots, \mathbf{Y}^{(N_u-1)^T}\right]^T = \boldsymbol{\Lambda}\mathbf{F}\mathbf{d} + \mathbf{W}, \tag{9}$$

where $\boldsymbol{\Lambda} \equiv \left[\boldsymbol{\Lambda}^{(0)^T}, \boldsymbol{\Lambda}^{(1)^T}, \cdots, \boldsymbol{\Lambda}^{(N_u-1)^T}\right]^T$ and $\mathbf{W} \equiv \left[\mathbf{W}^{(0)^T}, \mathbf{W}^{(1)^T}, \cdots, \mathbf{W}^{(N_u-1)^T}\right]^T$ are the aggregate channel matrix and aggregate noise vector, respectively. Since the aggregate channel matrix $\boldsymbol{\Lambda}$ is a random matrix, it has full rank with probability 1. With ZF criterion, the matrix product of $\boldsymbol{\Lambda} \times \mathbf{F}$ should be a $N_u|\mathfrak{I}_{(u)}|N_r \times N_u|\mathfrak{I}_{(u)}|N_r$ identity matrix, which requires that $\boldsymbol{\Lambda}$ has a full row rank of $N_u|\mathfrak{I}_{(u)}|N_r$. The pseudo-inverse of aggregate channel matrix $\boldsymbol{\Lambda}$ is given by

$$\mathbf{F} = \boldsymbol{\Lambda}^H(\boldsymbol{\Lambda}\boldsymbol{\Lambda}^H)^{-1}. \tag{10}$$

Now applying (10) to (9), the received signal vector at user u in (6) becomes the $K_{(u)}$ equivalent parallel channels:

$$Y_k^{(u)} = d_k^{(u)} + W_k^{(u)}, \qquad k = 0,1,\cdots,K_{(u)} - 1. \qquad (11)$$

C. J-MMSE preprocessing scheme

Just as ZF receivers eliminate the CCI at the cost of noise enhancement, the J-ZF pre-coding generally increases the average transmit power [8-9]. The J-MMSE preprocessing technique is another choice to make a good compromise between CCI cancellation and transmitter power efficiency. Base on the MMSE criterion [11], the aggregate preprocessing matrix $\mathbf{F}$ is given by $\mathbf{\Lambda}^H(\mathbf{\Lambda\Lambda}^H + (N_0/\rho)\mathbf{I})^{-1}$.

D. J-NSD preprocessing scheme

The idea behind J-NSD is to completely remove the CCI through projecting each user's signal vector away from other users' channel matrices. The design of preprocessing matrix $\mathbf{F}^{(u)}$ for user u is connected to the $(N_u - 1)|\Im_{(u)}|N_r \times |\Im_{(u)}|N_b N_t$ deflated version of aggregate channel matrix $\mathbf{\Lambda}$:

$$\mathbf{\Lambda}^{\overline{(u)}} \equiv \left[\mathbf{\Lambda}^{(0)^T},\cdots,\mathbf{\Lambda}^{(u-1)^T},\mathbf{\Lambda}^{(u+1)^T},\cdots,\mathbf{\Lambda}^{(N_u-1)^T}\right]^T. \qquad (12)$$

Let $\mathbf{V}^{\overline{(u)}}$ be the matrix composed of the last $|\Im_{(u)}|N_b N_t - K_{\overline{(u)}}$ right singular vectors of $\mathbf{\Lambda}^{\overline{(u)}}$, where $K_{\overline{(u)}}$ denotes the rank of $\mathbf{\Lambda}^{\overline{(u)}}$. Thus the columns of $\mathbf{V}^{\overline{(u)}}$ constitute the orthonormal bases for the null space of $\mathbf{\Lambda}^{\overline{(u)}}$, by which it is sure that $\mathbf{\Lambda}^{(u')}\mathbf{V}^{\overline{(u)}} = \mathbf{0}$ for $u' \neq u$.

Then we define the modified aggregate channel matrix for user u as $\mathbf{\Lambda}^{(u)'} \equiv \mathbf{\Lambda}^{(u)}\mathbf{V}^{\overline{(u)}}$, whose rank (also denoted by $K_{(u)}$) determines the dimension of data vector $\mathbf{d}^{(u)}$ that the N_b BSs cooperatively send to user u. The preprocessing matrix can be determined by $\mathbf{F}^{(u)} = \mathbf{\Lambda}^{\overline{(u)}}\mathbf{Q}^{(u)'}$, where $\mathbf{Q}^{(u)'}$ is a matrix composed of the first $K_{(u)}$ right singular column vectors of $\mathbf{\Lambda}^{(u)'}$, which constitute the orthonormal bases for the row space of $\mathbf{\Lambda}^{(u)'}$. Substituting $\mathbf{F}^{(u)} = \mathbf{\Lambda}^{\overline{(u)}}\mathbf{Q}^{(u)'}$ into (6) yields the following received vector at user u: $\mathbf{Y}^{(u)} = \mathbf{U}^{(u)'}\begin{bmatrix}\mathbf{\Sigma}^{(u)'} \\ \mathbf{0}\end{bmatrix}\mathbf{d}^{(u)} + \mathbf{W}^{(u)}$, where $\mathbf{U}^{(u)'}$ is a unitary matrix consisting of the left singular vectors of $\mathbf{\Lambda}^{(u)'}$ and $\mathbf{\Sigma}^{(u)'}$ is a $K_{(u)} \times K_{(u)}$ diagonal matrix whose diagonal entries are the $K_{(u)}$ non-zero singular values of $\mathbf{\Lambda}^{(u)'}$. Let $\sigma_k^{(u)'}$ denote the kth non-zero singular value. Transforming the received vector $\mathbf{Y}^{(u)}$ by the unitary matrix $\mathbf{U}^{(u)'H}$ results in the following $K_{(u)}$ equivalent parallel channels: $\tilde{Y}_k^{(u)} = \sigma_k^{(u)'}d_k^{(u)} + W_k^{(u)}$, $k = 0,1,\cdots,K_{(u)} - 1$.

IV. SIMULATION RESULTS

We present the performance comparison among different joint preprocessing techniques derived in Section 3. A convolutional code with a rate of 1/2 and a memory of 4 is applied to generate the coded bits. The IDFT/DFT size is 256, and the data symbols are modulated with quadrature phase shift keying (QPSK). The multipath channel between each BS b and user u is Rayleigh-faded with $L_{(b,u)} = 4$. For the path loss coefficient $K^{(b,u)} = \beta_0 d_{(b,u)}^{-\gamma}$, the propagation constant β_0 and path loss exponent γ are 1.35×10^7 and 3, respectively [11]. The radius of each cell is 1000 meters.

Unless otherwise stated, there are three users, each with single receive antenna, located around P1 (as shown in Fig. 1), and the number of transmit antennas N_t is 3. Fig. 2 shows the performance comparison between different joint preprocessing techniques. The J-TDMA without ICI and single-user (SU) processing without dealing with the ICI are given for performance benchmark. It is found that the BER performance of J-MMSE is close to the J-TDMA since it makes a good tradeoff between interference suppression and transmitter power efficiency. Just as ZF receivers enhance the noise power in order to completely remove the interference, J-ZF precoding also increases the average transmit power. Thus the performance of J-ZF is generally inferior to that of J-MMSE. For J-NSD transmission, each user's signal vector is projected away from other users' channel matrices. Thus it comes with a penalty in that a user's transmission is constrained to a smaller subspace. Nevertheless, the J-NSD significantly outperforms the SU upper-bound benchmark.

Fig. 3 gives the performance comparison for different number of receive antennas for J-TDMA and J-ZF. Note that the coordinated BSs can transmit up to $K_{(u)}$ $\left(= |\Im_{(u)}|N_r = 16N_r\right)$ independent data symbols for user u during each time of cooperative transmission. It is found that, for a given number of transmit antennas, as the number of receive antennas increase, the amount of transmitted data symbols increases but the extra degrees of freedom available for the joint preprocessing among coordinated BSs decrease. As shown in Fig. 3, as compared with single receive antenna, there exist about 2-dB and 4.5-dB loss in SNR at BER of 10^{-3} for J-TDMA and J-ZF, respectively, as increasing an additional receive antenna. The performance degradation can be improved through increasing the number of transmit antennas, N_t. Fig. 4 illustrates the influence of this increasing on the performance with $N_r = 2$. It is found that increasing the number of transmit antennas produces more degrees of freedom for joint preprocessing and thus can effectively improve the performance.

V. CONCLUSIONS

In this paper, we investigated several joint precoding techniques for multiple coordinated cell sites to address the serious CCI in DL CoMP broadband transmission. For a given number of transmit antennas, as the number of receive antennas increase, the per-user data rate increases as well but the extra degrees of freedom available for joint preprocessing decrease which results in performance degradation. This degradation can be improved through increasing the number of transmit antennas to raise the degrees of freedom. Simulation results show that for making a good tradeoff between interference suppression and transmitter power efficiency, the performance of J-MMSE is closest to the CCI-free J-TDMA approach. The J-ZF enables complete suppression of interference but its performance is inferior to that of J-MMSE due to the increase of power required on preprocessing matrix. In J-NSD, each user's signal vector is constrained to a smaller subspace in order to entirely null out other users' signals and it significantly outperforms the SU upper-bound benchmark.

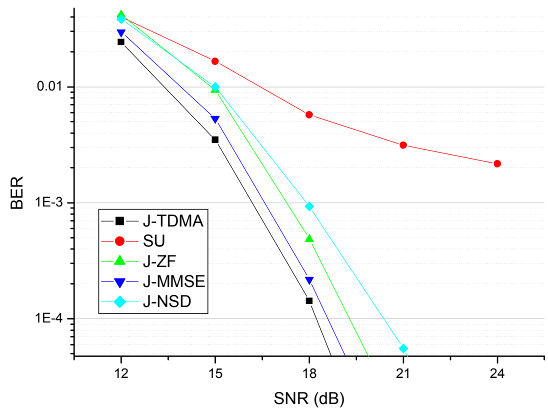

Fig. 2 BER performance comparison for different JP/JT techniques

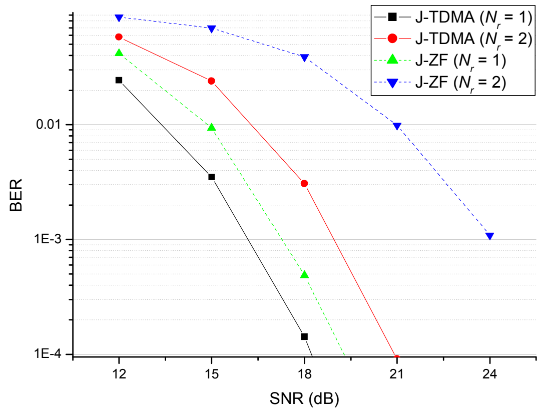

Fig. 3 BER performance comparison for different number of receive antennas

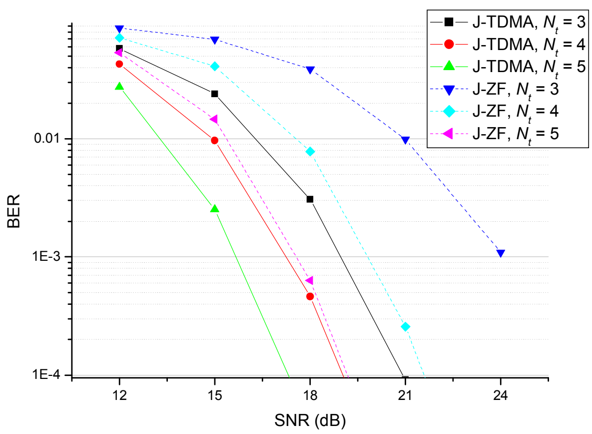

Fig. 4 Influence of increasing the number of transmit antennas on the performance with $N_r = 2$

REFERENCES

[1] G. Boudreau, J. Panicker, N. Guo, R. Change, N. Wang, and S. Vrzic, Nortel, "Interference coordination and cancellation for 4G networks," *IEEE Commun. Mag.*, vol. 47, no. 4, Apr. 2009, pp. 74-81.

[2] 3GPP TR 36.814, "Further Advancements for E-UTRA," v. 1.5.2, Dec. 2009; ftp://ftp.3gpp.org

[3] M. K. Karakayali, G. J. Foschini, and R. A. Valenzuela, "Network Coordination for Spectrally Efficient Communications in Cellular Systems," *IEEE Wireless Commun.*, vol. 13, no. 4, Aug. 2006.

[4] J. G. Andrews, W. Choi, and R. W. Heath Jr., "Overcoming Interference in Spatial Multiplexing MIMO Cellular Networks," *IEEE Wireless Commun.*, vol. 14, no. 6, Dec. 2007, pp. 95–104.

[5] M. Sawahashi, Y. Kishiyama, A. Morimoto, D. Nishikawa, and M. Tanno, "Coordinated multipoint transmission/reception techniques for LTE-Advanced," *IEEE Wireless Commun.*,, vol. 17, no. 3, June 2010, pp. 26-34.

[6] A. Ghosh, R. Ratasuk, B. MOndal, N. Mangalvedhe, and T. Thomas, "LTE-Advanced: Next-Generation Wireless Broadband Technology," *IEEE Wireless Commun.*,, vol. 17, no. 3, June 2010, pp. 10-22.

[7] S. Shamai and B.M. Zaidel, "Enhancing the cellular downlink capacity via co-processing at the transmitting end," in *Proc. Spring IEEE 53rd Vehicular Technology Conference (VTC '01)*, vol. 3, pp. 1745–1749, Rhodes, Greece, May 2001.

[8] H. Zhang and H. Dai, "Cochannel interference mitigation and cooperative processing in downlink multicell multiuser MIMO networks," *EURASIP Journal on Wireless Communications and Networking*, pp. 222-235, February 2004.

[9] G.J. Foschini, K. Karakayali and R.A. Valenzuela, "Coordinating multiple antenna cellular networks to achieve enormous spectral efficiency," *IEE Proc.-Commun.*, vol. 153, no. 4, Aug. 2006, pp. 548-555.

[10] M. Costa, "Writing on dirty paper," *IEEE Transactions on Information Theory*, vol. 29, no. 3, pp. 439–441, 1983.

[11] T.S. Rappaport, *Wireless Communications Principles and Practice* , 2nd Ed., Prentice Hall, 2003.