MU-MIMO Downlink Scheduling Based On Users' Correlation and Fairness

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***Abstract*—A scheduling algorithm based on weighted users' correlation and fairness (WUCFS) is proposed for MU-MIMO downlink broadcast channels (BC), to address the problem that traditional fairness scheduling algorithms cannot handle, i.e., they cannot accurately compute the achievable rate for each user in their iterative user selection process, thus creating an undesirable tradeoff between user fairness and system sum-rate. The proposed WUCFS is used to activate mobile subscribers by evaluating the correlation between the candidate and the selected users as well as those who may be scheduled for data transmission. Weighted inverse-correlation maximization is then employed to determine which users to be scheduled for data transmission. By estimating potential co-channel interference (CCI) *a priori*, our algorithm can accurately estimate the actual transmission rate of each mobile user, and fairly activate a set of users with small mutual interference. Compared to existing schemes, the proposed algorithm is shown to improve fairness among users while ensuring high system sum-rate.**

Keywords—Multi-user MIMO system; co-channel interference; correlation; fairness

I. INTRODUCTION

As a key technology for future mobile communications, multi-input multi-output (MIMO) can significantly improve spectral efficiency and transmission reliability without extra bandwidth demand [1]. Compared to single-user MIMO (SU-MIMO), multi-user MIMO (MU-MIMO) is better suited for real-world communications and can achieve higher system data-rates, thus drawing significant attention [2].

In a MU-MIMO system, due to its hardware constraints and limited processing capability, the base station (BS) needs to select a set of users from a large pool of candidate users to serve simultaneously. The active mobile stations (MSs) share the same frequency band employing spatial multiplexing [3]. However, due to co-channel interference (CCI), the achievable system sum-rate is dependent on inter-correlation among multiple active users. Thus, selection of a group of MSs with small mutual interference becomes an important problem. If BS can acquire full channel state information (CSI), it can find an optimal solution by exhaustively searching all subsets of users to be served simultaneously, but such an approach will be too complex to be useful. In order to reduce the complexity, suboptimal greedy algorithms have been proposed [4-8]. In contrast to the exhaustive search of all possible subsets of users to be served simultaneously, the basic idea of greedy algorithms is to select users iteratively, one at a time that best fits the scheduling criterion. Of the studies related to this, the authors of [4] proposed a semi-orthogonal user selection (SUS) algorithm based on channel correlation, under which the user with the largest channel gain is scheduled first. Then, in each iteration it determines a user set, the orthogonality degree between users in which and those added in the last scheduling iteration exceeds a pre-set threshold. Then, it selects the user from the user set with the largest projection component on the subspace orthogonal to the one spanned by the channels corresponding to the activated users. The authors of [5] improved the results of [4], where users are optimally scheduled based on direction channel information and the parameter that controls inter-user orthogonality. In [6] a method with lower-complexity than that in [4] is presented without degrading system sum-rate. In [7] antenna selection is designed based on channel correlation. The cooperative capability of different antennas of the same user is exploited to determine the antenna set, maximizing system sum-rate. In [8], block diagonalization is employed. With the objective of maximizing system sum-rate, the user creating the smallest correlation with the selected users is scheduled.

In the above-mentioned approaches, users are activated based on minimizing inter-user correlation and maximizing system sum-rate is the design objective. However, when users experience different fading conditions, as is usually the case, the algorithms proposed in [4-8] are likely to select users with good channel conditions, leaving those with poor channel conditions starved. This will result in unfairness among users. Proportional fair (PF) scheduling takes users fairness into account [9], where the ratio of the user's current data rate to his average rate is used as priority. PF could achieve a tradeoff between system sum-rate and users fairness. Nevertheless, due to the sequential users scheduling of the greedy algorithms [4-8], the achievable rate of each user cannot be achieved until the last user is activated. Hence, how to evaluate the accurate data rate of each user during the iterative process becomes a critical issue [4, 10-11]. In [4] CCI among semi-orthogonal users is neglected, and Frobenius norm of the projection of the candidate user channel on the subspace orthogonal to the one spanned by the selected users' channel matrices is calculated as the gain, according to which the achievable rate for each user is determined. In [10] the PF is applied based on Frobenius norm of each user's channel matrix, whereas in [11], the rate is calculated using the product of the squared Frobenius row norms in the user's channel matrix instead of the eigenvalues.

Unfortunately, the above approaches are still inaccurate in estimating the user's achievable rate during the iteration process, introducing an undesirable tradeoff between fairness and system rate performance. Meanwhile, the scheduling mechanisms based on user channel spatial correlation [4-5, 8] may cause CCI between the *n*-th user and the selected (*n*-1) users to be small, but yield a large CCI with the other candidates, i.e., all remaining users cannot coexist well with the *n*-th user under investigation. Consequently, the system sum-rate is deteriorated [12]. In [4, 10-11], the user with the largest channel gain among all the candidates is selected successively. This criterion may cause severe CCI due to strong correlation among multiple users, thus resulting in poor sum-rate performance.

In order to solve the above problems, a fairness scheduling algorithm based on weighted users' correlation (WUCFS) is proposed in this paper. Correlation between candidate and the selected users as well as those who may be scheduled is considered together. Then, each correlation value is assigned along with a weight for fairness. The proposed algorithm achieves better fairness among users while ensuring high system sum-rate.

Throughout this paper, we use the following notation. The set of complex numbers is denoted as $\mathbb{C}$, while vectors and matrices are represented by bold lower-case and upper-case letters, respectively. $\mathrm{E}(\cdot)$ denotes statistical expectation. The Hermitian (or conjugate transpose) of a vector or a matrix and conjugate of a complex number are denoted as $(\cdot)^H$ and $(\cdot)^*$, respectively. The Euclidean norm of a vector or a matrix is denoted as $\|\cdot\|$, whereas $|\cdot|$ denotes the absolute value of a scalar number. $\langle \boldsymbol{a},\boldsymbol{b}\rangle$ represents for the inner product of two vectors.

II. SYESTM MODEL

Consider a single-cell MU-MIMO downlink broadcast channels consisting of a base station (BS) and L mobile stations (MS). Let N_T and N_R be the numbers of antennas at BS and each MS, respectively. BS selects K out of L MSs to serve simultaneously during a downlink transmission period.

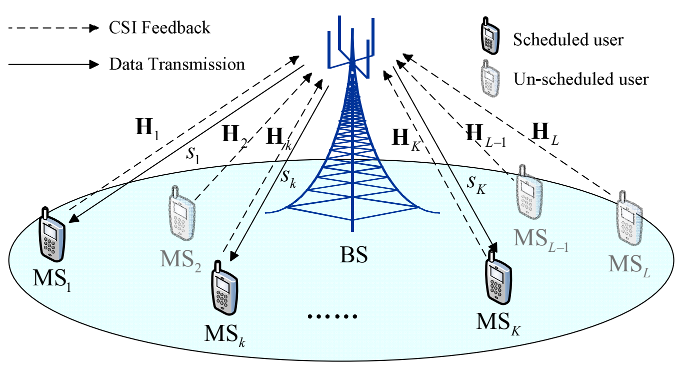

Fig. 1. System model

Let $\mathcal{A}$ denote the set of candidate users to serve, $\mathrm{card}(\mathcal{A}) = L$ where $\mathrm{card}(\cdot)$ represents the cardinality of a set, and let $\mathcal{S}$ be the set of active users, and $\mathrm{card}(\mathcal{S}) = K$. In practice, L is always larger than N_T. Due to hardware constraints and limited processing capability, the number of active users K should meet the condition $K \le N_T$ such that the feasibility of CCI elimination by designing proper precoding is fulfilled [11]. In this paper we focus on user scheduling which can be treated as a stage prior to the precoder design, so the later part at BS for CCI cancellation is not investigated. For simplicity, let $N_R = 1$. The total transmit power of BS is P_T.

Let $\boldsymbol{H}_k$ denote the channel matrix from BS to MS_k. A spatially uncorrelated Rayleigh flat fading channel model is assumed so that the elements of $\boldsymbol{H}_k$ may be modeled as independent and identically distributed zero-mean unit-variance complex Gaussian random variables. We assume that all users experience block fading, i.e., channel parameters in a block consisting of several successive transmission cycles, each cycle of length T, remain constant within the block and vary randomly between blocks. Each user can accurately estimate CSI and provide feedback to BS via a low-rate error-free link. Based on channel reciprocity, BS could utilize the feedback information to schedule users. The time length T is different for different applications: for example, in GSM $T = 0.577\mathrm{ms}$ whereas in TD-LTE $T = 0.5\mathrm{ms}$. During a transmission cycle, BS first sends a training sequence to MSs, then collects CSI, selects users, and finally performs data communication. The processes before data transmission take a finite amount of time τ is called an *overhead slot*. In the case of downlink, sending training sequences constitutes the main part of total overhead. A typical value of τ / T ranges from 5 to 10% [13]. Since τ is small relative to T, we omit the discussion of this overhead.

III. BASIC SIGNAL PROCESSING IN MU-MIMO BC

In this section we present fundamental processing in MU-MIMO BC. Note that BS schedules simultaneous transmission by K MSs out of L candidates. The signal received at user k, $k \in \mathcal{S}$ is given by:

$$y_k = \boldsymbol{H}_k \boldsymbol{x} + n_k \tag{1}$$

where $\boldsymbol{x}$ denotes the signal vector transmitted from BS to users belonging to $\mathcal{S}$. The average power constraint $\mathrm{E}(\|\boldsymbol{x}\|^2) = P_T$ holds for BS and n_k is the additive white Gaussian noise (AWGN) with zero-mean and variance σ_n^2. Assume BS employs beamforming (BF) for each MS in downlink transmission. The symbol transmitted to MS_k is denoted by s_k. So the transmitted signal is $\boldsymbol{x} = \sum_{k \in \mathcal{S}} \boldsymbol{w}_k s_k$ where $\boldsymbol{w}_k \in \mathbb{C}^{N_T \times 1}$ is the precoding vector for user *k*. Consequently, the received signal at MS_k is rewritten as:

$$y_k = \boldsymbol{H}_k \boldsymbol{w}_k s_k + \boldsymbol{H}_k \sum_{j \in \mathcal{S}, j \ne k} \boldsymbol{w}_j s_j + n_k \tag{2}$$

The first part in the right hand side (RHS) of (2) represents the expected signal at user k, whereas the second term denotes the interference from the other active users.

Applying the singular value decomposition (SVD) to $\boldsymbol{H}_k$, we get $\boldsymbol{H}_k = \boldsymbol{U}_k \boldsymbol{\Lambda}_k \boldsymbol{V}_k^H = u_k \left[\lambda_{k,1} \quad \mathbf{0}_{N_T-1}\right]\left[\boldsymbol{V}_k^{(1)} \quad \boldsymbol{V}_k^{(0)}\right]^H$ where $\mathbf{0}_{N_T-1}$ is a $1\times(N_T-1)$ zero matrix, $\boldsymbol{V}_k^{(1)}$ and $\boldsymbol{V}_k^{(0)}$ consists of the right singular vectors corresponding to nonzero and zero singular values, respectively. Using the precoding vector $\boldsymbol{w}_k = \boldsymbol{V}_k^{(1)}$ and the receiving filter coefficient $f_k = u_k^*$, the estimated signal at MS_k is expressed as:

$$\tilde{y}_k = f_k y_k = \lambda_{k,1} s_k + \lambda_{k,1}\left[\boldsymbol{V}_k^{(1)}\right]^H \sum_{j\in\mathcal{S}, j\neq k} \boldsymbol{V}_j^{(1)} s_j + \tilde{n}_k \quad (3)$$

where $\tilde{n}_k = u_k^* n_k$. Since the modulus of u_k is 1, the variance of $\tilde{n}_k$ remains σ_n^2.

The total transmit power P_T is assumed equally distributed over $K = N_T$ beams (sub-channels) corresponding to $K = N_T$ active users. For each beam, the transmit power is $P_0 = P_T / N_T$. The SINR of user k is calculated as:

$$\gamma_k = \frac{P_0 \lambda_{k,1}^2}{\sigma_n^2 + \chi_k} \quad (4)$$

χ_k denotes the co-channel interference.

$$\chi_k = \lambda_{k,1}^2 \mathrm{E}\left\{\left\{\sum_{j\in\mathcal{S}, j\neq k}\left[\boldsymbol{V}_k^{(1)}\right]^H \boldsymbol{V}_j^{(1)} s_j\right\}\left\{\sum_{j\in\mathcal{S}, j\neq k}\left[\boldsymbol{V}_k^{(1)}\right]^H \boldsymbol{V}_j^{(1)} s_j\right\}^H\right\} \quad (5)$$

Due to the statistical independence of transmit symbols, (6) is obtained as:

$$\mathrm{E}(s_m s_n^H) = \begin{cases} 0, & m \neq n \\ P_0, & m = n \end{cases} \quad (6)$$

Then, (5) can be simplified as:

$$\chi_k = \lambda_{k,1}^2 P_0 \sum_{j\in\mathcal{S}, j\neq k}\left|\left[\boldsymbol{V}_k^{(1)}\right]^{\mathrm{H}} \boldsymbol{V}_j^{(1)}\right|^2 \quad (7)$$

Note that the spatial feature of different beams related to active MSs is not mutually orthogonal, so the transmission from BS to MS_k is affected by the transmissions from BS to other selected MSs. The achievable rate of MS_k is given by:

$$R_k = \log_2(1+\gamma_k) \quad (8)$$

The total system sum-rate is calculated by:

$$R_{sum} = \sum_{k\in\mathcal{S}} R_k \quad (9)$$

IV. WEIGHTED USERS' CORRELATION AND FAIRNESS BASED SCHEDULING

Based on the discussion in Section III, a set of users with as small mutual interference as possible should be selected to achieve high system sum-rate. However, this criterion may let users with good channel condition occupy channel resource continuously while starving those with poor channel quality. PF is an effective way to ensure the fairness among users [9]. But the difficulty in applying PF in the above-mentioned greedy algorithms [4-8] is that users are activated sequentially, and hence the accurate SINR and achievable data rate of selected users cannot be acquired until the last user is activated. In other words, before the set $\mathcal{S}$ is determined, the calculations based on (4), (5) and (7) are not accurate.

As discussed in the Introduction, accurate estimation of user data rate is critical to achieving good fairness and high system throughput. In this section, we propose a scheduling algorithm based on weighted users' correlation and fairness (WUCFS) to achieve accurate estimation of user rates by considering the interference between candidate and selected MSs as well as those that may be scheduled. Then, the weighting factors are determined to achieve both high system sum-rate and good fairness performance.

Aiming to maximize the weighted sum-rate, PF can be described as [14]:

$$\max_{\mathcal{S}\subset\mathcal{A}} \sum_{k\in\mathcal{S}} \mu_k(t) R_k(t) \quad (10)$$

$\mu_k(t) = 1/\bar{R}_k(t)$ and $R_k(t)$ are the weighting factor and the achievable rate of user k during the *i*-th transmission cycle. Note that when $\mu_k(t)=1$, the maximization problem (10) is equivalent to maximizing the system sum-rate. $\bar{R}_k(t)$ denotes the average rate achieved by MS_k up to transmission cycle $t-1$, which is updated as [14]:

$$\bar{R}_k(t+1) = \begin{cases} \delta_c \bar{R}_k(t) + (1-\delta_c) R_k(t), & k\in\mathcal{S} \\ \delta_c \bar{R}_k(t), & k\notin\mathcal{S} \end{cases} \quad (11)$$

where δ_c acts as a forgetting factor. For the average rate of each user over an observation window of T_c time slots, δ_c is defined as $\delta_c = 1 - 1/T_c$. When MS_k experiences poor channel condition, i.e., $R_k(t)\to 0$, the larger T_c, the more slowly the average sum-rate is updated. Then, it will take a long time for MS_k to get an opportunity to be scheduled. In this paper, we set δ_c=0.99 [10].

As can be seen from (4) and (7), given P_T and σ_n^2, the smaller $\psi_k^{-1} = \sum_{j\in\mathcal{S}, j\neq k}\left|\left[\boldsymbol{V}_k^{(1)}\right]^H \boldsymbol{V}_j^{(1)}\right|^2$, the larger SINR of MS_k and the higher achievable sum-rate. Therefore, a scheduling algorithm can be designed based on the correlation value ψ_k^{-1}. However, it should be noted that until the entire scheduling process is completed, the exact value of ψ_k^{-1} cannot be obtained. On the other hand, in order to improve system sum-rate, users should be selected based on not only the correlation between candidate and selected users, but also the interference between candidate users and those that may be scheduled [12]. Based on the above analysis, we do not neglect the CCI, but consider potential additional interference. As a result, ψ_k^{-1} can be estimated more accurately.

According to the above discussion, the estimation of the achievable user rate is converted to the calculation of $\psi_{k,n}$ in the *n*-th MS scheduling step, as given as:

$$\psi_{k,n}^{-1} = \min_{\substack{\mathcal{A}_l \subset \mathcal{A}_{n-1},\\ \mathrm{card}(\mathcal{S}_{n-1})+\mathrm{card}(\mathcal{A}_l)=\xi}} \left\{ \sum_{k\in\mathcal{A}_{n-1}, j\in\mathcal{S}_{n-1},} \left| \left[\boldsymbol{V}_k^{(1)}\right]^H \boldsymbol{V}_j^{(1)} \right|^2 + \sum_{k\in\mathcal{A}_{n-1}, m\in\mathcal{A}_l, k\neq m} \left| \left[\boldsymbol{V}_k^{(1)}\right]^H \boldsymbol{V}_m^{(1)} \right|^2 \right\} \tag{12}$$

where $\mathcal{A}_{n-1}$ and $\mathcal{S}_{n-1}$ are the sets of candidate and selected users in the (*n*-1)-th step, respectively. $\mathcal{A}_l$ denotes the set of users that may be scheduled. The first term in the RHS of (12) indicates the existing interference, whereas the second term represents potential interference. The choice of parameter ξ affects both the system sum-rate and the complexity. For a small value of ξ, a group of users with high CCI may be selected due to the underestimation of potential interference. When ξ is chosen to be too large, the achievable sum-rate may also be deteriorated since too many unnecessary factors are taken into account. In Section V, proper selection of ξ will later be demonstrated via simulation.

Taking an arbitrary transmission cycle t ($t = 1,2,\cdots$) as an example, the operation of WUCFS at BS in the *overhead slot* τ is detailed as follows. (For simplicity, the time index t is omitted.)

Step 1) Initialize $\mathcal{S}_0 = \varnothing$, $\mathcal{A}_0 = \{1,\cdots,L\}$ and $n=1$ where $\varnothing$ denotes the null set. $\mathcal{A}_n$ and $\mathcal{S}_n$ indicate the sets of candidate and selected users the end of the *n*-th iteration. $n = 1,\cdots,N_T$ represents for iteration times.

Step 2) BS performs SVD on $\boldsymbol{H}_k$ according to the feedback from MS_k, $\boldsymbol{H}_k = \boldsymbol{U}_k \boldsymbol{\Lambda}_k \boldsymbol{V}_k^H = u_k \left[\lambda_{k,1} \quad \boldsymbol{0}_{N_T-1}\right] \left[\boldsymbol{V}_k^{(1)} \quad \boldsymbol{V}_k^{(0)}\right]^H$. According to the analysis in Section II, $\mathrm{rank}(\boldsymbol{H}_k) = 1$. Thus, $\boldsymbol{V}_k^{(1)} = \boldsymbol{v}_{k,1}$ where $\boldsymbol{v}_{k,1}$ is the first column of $\boldsymbol{V}_k^{(1)}$.

Step 3) Construct matrix $\hat{\boldsymbol{V}} = \left[\boldsymbol{V}_1^{(1)}, \boldsymbol{V}_2^{(1)}, \cdots, \boldsymbol{V}_L^{(1)}\right]$ and $\hat{\boldsymbol{\Lambda}} = \mathrm{diag}\left[\lambda_{1,1}, \lambda_{2,1}, \cdots, \lambda_{L,1}\right]$ where $\mathrm{diag}(\cdot)$ denotes diagonalization operation.

Step 4) Calculate the correlation matrix $\boldsymbol{R}_n$. $\boldsymbol{R}_n$ is an $L\times L$ square matrix whose element in the *k*-th row and the *j*-th column is denoted by $r_{k,j} = \left| \left[\boldsymbol{V}_k^{(1)}\right]^H \boldsymbol{V}_j^{(1)} \right|^2$.

Step 5) Select $n-1$ columns of $\boldsymbol{R}_n$ corresponding to the selected $n-1$ users to form $\boldsymbol{R}_n^{\mathcal{S}_{n-1}}$. Each row of the remaining part of $\boldsymbol{R}_n$ is arranged in ascending order to form another matrix $\boldsymbol{R}_n^{\mathcal{A}_{n-1}}$. Then, $\boldsymbol{R}_n$ is reconstructed as $\boldsymbol{R}_n = \left[\boldsymbol{R}_n^{\mathcal{S}_{n-1}} \quad \boldsymbol{R}_n^{\mathcal{A}_{n-1}}\right]$.

Step 6) Calculate $\psi_{k,n}^{-1}$ based on (12). $\psi_{k,n}^{-1}$ is the sum of the first ξ elements of each row in $\boldsymbol{R}_n$, which is equivalent to a simplified expression as:

$$\psi_{k,n}^{-1} = \sum_{j=1}^{\xi} r_{k,j} \tag{13}$$

Step 7) Select user n according to

$$s_n = \arg\max_{k\in\mathcal{A}_{n-1}} \mu_k \psi_{k,n} \tag{14}$$

where s_n denotes the index of the selected user. $\mu_k = 1/\bar{\psi}_{k,t-1}$ is the weight and $\bar{\psi}_{k,t-1}$ is the averaged inverse-correlation for MS_k until the end of the last transmission cycle. Update $\mathcal{S}_n := \mathcal{S}_{n-1} \cup \{s_n\}$, $\mathcal{A}_n := \mathcal{A}_{n-1} - \{s_n\}$ and $n := n+1$.

If $n < N_T$, then return to Step 5 else terminate the scheduling process for the upcoming transmission cycle. BS calculates the inverse-correlation value ψ_{k,N_T} for activated user k ($k \in \mathcal{S}_{N_T}$) based on the actual interference it suffers from. If the user is not scheduled, i.e., $k \notin \mathcal{S}_{N_T}$, $\psi_{k,N_T} = 0$. The averaged inverse-correlation value $\bar{\psi}_{k,t}$ is initialized at the starting point of t with a small positive value, and updated according to the following rule, which will be used for calculation of the user weight in the next transmission cycle with index $t+1$.

$$\bar{\psi}_{k,t} = \begin{cases} \delta_c \bar{\psi}_{k,t-1} + (1-\delta_c)\psi_{k,N_T}, & k \in \mathcal{S}_{N_T} \\ \delta_c \bar{\psi}_{k,t-1}, & k \notin \mathcal{S}_{N_T} \end{cases} \tag{15}$$

After completing the scheduling of users, BS notifies the active users and performs downlink transmission. In the overhead slot of the following transmission cycle, BS repeats Steps 1-7. Note that BS should also maintain the information of $\bar{\psi}_{k,t}$ for each MS during the entire downlink communication to achieve fairness.

The user scheduling criterion based on CCI minimization may hinder selection of those users of high interference to the others. In order to allow those users equal access to communication resources, a weight $\mu_k = 1/\bar{\psi}_{k,t-1}$ is assigned to the correlation of user k in transmission cycle t in the proposed algorithm. During each cycle, BS calculates ψ_k and updates $\bar{\psi}_{k,t}$ according to (15). Users are scheduled according to (14). The averaged correlation $\bar{\psi}_{k,t}$ of the frequently selected users grows and the weight value μ_k decreases with time, thereby lowering their scheduling priority. The users of high interference to the others are not activated at first due to the CCI minimization criterion, but their $\bar{\psi}_{k,t}$ decreases and correspondingly μ_k increases with time, thus increasing their scheduling priority.

V. Simulation Results

We now evaluate the performance of proposed mechanism (WUCFS) in comparison with six other algorithms, including exhaustive scheduling (ES), semi-orthogonal user selection (SUS) [4], proportional fair SUS (PF-SUS) with which the user of the largest ratio of current achievable data rate to its average rate is scheduled in each iteration, reactive scheduling (RS) [15] with which users are scheduled based on the interference between candidate and selected users, proactive scheduling (PS) [12] which investigates the interference between candidate users and those who may be scheduled, and extended PF (ePF) which is originally applied to the scenario where only one user is activated in each transmission cycle and here it is used in the situation where multiple users are scheduled simultaneously, but CCI is ignored for simplicity, hence resulting in inaccurate rate computation.

Fig. 2 shows the impact of ξ on system sum-rate normalized by transmission bandwidth with WUCFS under $\mathrm{SNR}=10\mathrm{dB}$, $L=30$ and different values of N_T. The optimal value of ξ corresponding to the maximum sum-rate is marked as solid pentagram. The optimal or near optimal normalized sum-rate is achieved when $\xi = N_T - 1$. Due to space limitation, results under different parameters are not shown. However similar conclusion can be drawn.

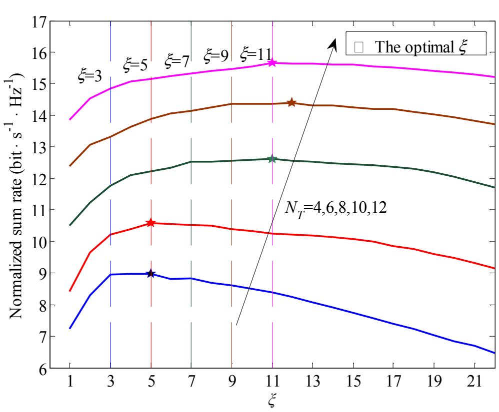

Fig. 2. Normalized sum-rate versus ξ under $\mathrm{SNR}=10\mathrm{dB}$, $L=30$ and different N_T.

Fig. 3 shows the normalized sum-rate in comparison of multiple algorithms for different SNRs under $N_T=4$ and $L=8$. ES is shown to achieve the best rate performance. When $\mathrm{SNR}<-5\mathrm{dB}$, the rate of user transmission is dominated by channel gain $\lambda_{k,1}$ based on (4), (7) and (8), so the difference between multiple algorithms is relatively small. As SNR increases, co-channel interference χ_k gradually dominates the sum-rate. Given $P_T/(N_T\sigma_n^2)$, the smaller χ_k, the higher system sum-rate. RS, SUS and PF-SUS only consider interference between candidate and selected users. Since RS selects user n of minimum mutual interference to the $n-1$ activated users, a set of MSs with small CCI could be achieved. The rate performance of RS is inferior to that of PF-SUS due to the fact that RS does not take channel gain into consideration in user scheduling. SUS selects MS based on the orthogonality between the candidate and the latest added user, which may result in the situation where the mutual interference between active user n and user $n-1$ is small, yet the CCI between user n and the previous selected $n-2$ users is severer. Although channel gain is considered in SUS, the scheduling rationality of SUS is not as good as that of RS. As for PF-SUS, channel gain is also considered in user scheduling. It yields better rate performance than RS and SUS. However, PF-SUS treats semi-orthogonal users as orthogonal, and this improper approximation makes its normalized rate inferior to that of WUCFS. The proposed mechanism takes the interference between candidate users and those to be selected potentially into account, thus achieving better performance than RS, SUS, and PF-SUS in a high SNR region. Similar to WUCFS, potential CCI evaluation is involved in PS, but user fairness is ignored. ePF outputs the worst rate performance due to the fact that the CCI is ignored inappropriately and consequently affects the scheduling results.

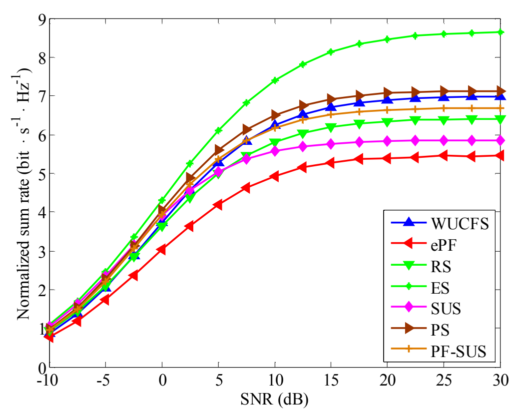

Fig. 3. Normalized sum-rate versus different SNRs under $N_T=4$ and $L=8$.

Fig. 4 illustrates the comparison of fairness among different algorithms versus the number of users L under $N_T=4$ and $\mathrm{SNR}=10\mathrm{dB}$. This evaluation is based on Jain's fairness index (FI) [16], which indicates the degree of satisfaction of different users with respect to its traffic demand.

$$\mathrm{FI}=\left(\sum_{k=1}^{L}\varphi_k\right)^2\Bigg/\left(L\sum_{k=1}^{L}\varphi_k^2\right) \tag{16}$$

where φ_k is the scheduled frequency of user k in a given time period. The value of FI is within the range [0,1]. The larger FI, the better fairness. If all users get an equal chance to be scheduled, $\mathrm{FI}=1$, whereas if only one user is scheduled, $\mathrm{FI}=1/L$. It can be seen from Fig. 4 that with WUCFS and ePF, FI varies between 0.9 and 1 indicating good fairness. As for the other algorithms, FI decreases with increasing L, i.e. the fairness deteriorates as the number of users increases.

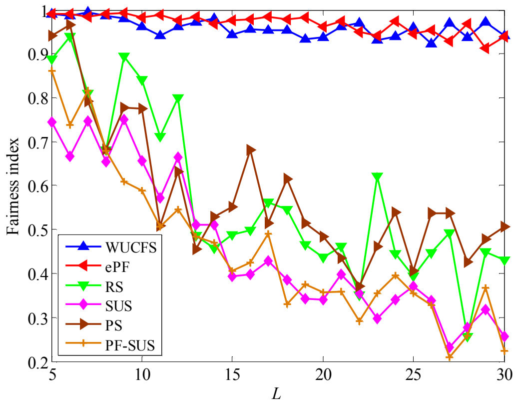

Fig. 4. Comparison of fairness index versus L under $N_T = 4$ and $\text{SNR} = 10\text{dB}$.

In Fig. 5, the cumulative distribution functions (CDF) with different methods under $N_T = 4$, $\text{SNR} = 10\text{dB}$ and $L = 30$ are plotted. It shows that with PS, RS, SU and PF-SUS, approximately 32%, 40%, 70% and 3% of total users cannot access transmission service, respectively. For WUCFS and ePF, all users could obtain schedule opportunities. However, being provided with the same CDF, WUCFS outperforms ePF in terms of average bandwidth-normalized user rate. For example, with WUCFS about 60% of users can achieve $0.26\text{bit.s}^{-1}.\text{Hz}^{-1}$ whereas with ePF it is only $0.19\text{bit.s}^{-1}.\text{Hz}^{-1}$.

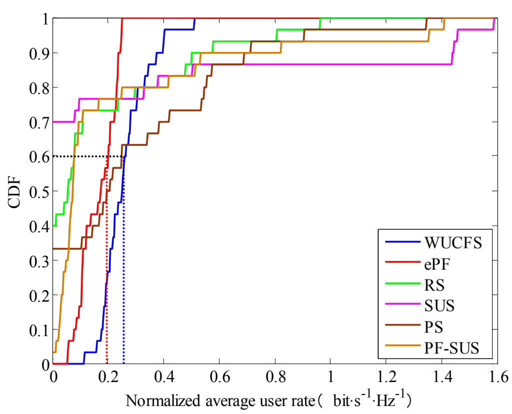

Fig. 5. Comparison of CDF under $N_T = 4$, $\text{SNR} = 10\text{dB}$, $L = 30$.

VI. Conclusion

In this paper, a fairness scheduling algorithm based on weighted users' correlation (WUCFS) is proposed for MU-MIMO downlink broadcast channels. Correlation between candidate and selected users as well as those who may be scheduled is taken into account. Then, each correlation value is assigned with a weight for fairness control. Since the achievable user rate can be estimated more accurately, a set of users with small mutual interference can be scheduled with better fairness and appropriateness. Compared to existing methods, the proposed mechanism could achieve a higher system sum-rate while maintaining good fairness.

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