# A Joint Adaptive Beamforming and User Scheduling Algorithm for Downlink Network MIMO Systems

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***Abstract*—In this paper, we study multiple-input single-output downlink cellular systems which jointly design adaptive inter-cell interference cancellation and user scheduling assuming that partial channel state information (CSI) is shared among base stations (BSs). Since the optimal solution requires high complexity, we propose a new low complexity algorithm which selects the best users and their beamforming (BF) strategies in terms of maximizing the weighted sum rate. To this end, we first develop a simple threshold criterion for each user to decide the preferred BF strategy based on the derivation of the expected signal-to-interference-plus-noise ratio. Then, according to users' feedback about their decisions, a successive user and BF selection algorithm is performed at the BSs. From simulation results, we show that combined with proportional fair scheduling, the proposed scheme provides excellent sum rate performance with very low computational complexity.**

## I. Introduction

Over the past decade, wireless cellular technologies have continuously evolved to accommodate extremely high spectral efficiencies through utilization of multiuser multiple-input multiple-output (MIMO) techniques [1] [2]. Many research efforts have been focused on the single cell scenario, owing to information theoretic results of MIMO Gaussian broadcast channels (BCs) [3] [4]. In order to improve the sum rate, a variety of multiuser MIMO schemes have been proposed especially for downlink channels [5] [6].

On the other hand, next generation 4G systems such as LTE-advanced and IEEE 802.16m WiMAX are designed to support frequency reuse-1 mechanisms. Therefore, inter-cell or inter-sector interference is a major concern of future cellular systems. Recently, base station (BS) coordination strategies, called network MIMO or coordinated multiple point transmission (CoMP), have been proposed to increase the system and cell edge throughput by properly mitigating the inter-cell interference (ICI). The CoMP techniques are categorized into two scenarios, i.e., joint processing (JP) and coordinated scheduling/beamforming (CS/CB). One major challenge of the JP system [7] is the bandwidth limitation of backhaul links, which may not allow the BSs to exchange user data traffics in real-time. Therefore, researches are focused more on the CS/CB scenario, including a well-known information theoretic model of "interference channels" [8] [9] or interfering broadcast channels [10]. However, despite its necessity in real systems, relatively few efforts have been devoted to the development of inter-cell joint user selection policies.

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Recently, the authors in [11] proposed a new transmission strategy named as adaptive ICI cancellation (ICIC) for downlink CS/CB systems. Instead of adopting complicated beamforming (BF) solutions, they propose a scheme which adaptively chooses BF strategies between the two classic methods, i.e., single-cell BF and zero-forcing BF (ZFBF).

In this paper, we investigate an efficient adaptive ICIC strategy for MISO downlink CS/CB systems where multiple users exist in each cell. Since it is difficult to solve the joint problem of choosing the best user set and the strategy set for all BSs, we develop a new low complexity algorithm for the user and BF strategy selection. To this end, we first propose a simple threshold criterion based on the expected signal-to-interference-plus-noise ratio (SINR) to decide a preferred BF strategy at each user terminal, which is fed back to the BS. Then, based on the feedback, a simple successive user and BF selection algorithm is carried out at the BSs. Numerical results verify that the proposed adaptive ICIC technique provides good sum rate performance with very low complexity.

Throughout this paper, we use the following notations. Normal letters represent scalar quantities, bold face letters indicate vectors, and boldface uppercase letters designate matrices. The superscript $(\cdot)^H$ stands for Hermitian transpose and the two-norm of a vector is denoted by $\|\cdot\|$. An $N \times N$ identity matrix is defined by $\mathbf{I}_N$ and the expectation operation is given as $\mathbb{E}[\cdot]$.

## II. System Model

We consider an $M$-cell downlink wireless network where BSs perform coordinated single-cell transmission, i.e., CoMP CS/CB systems. Figure 1 illustrates a three-cell network model as an example. Each BS is equipped with $N_t$ transmit antennas and communicates to $K$ users with a single antenna. The BSs are connected via high speed but limited bandwidth backhaul links with no delay, from which they exchange a certain level of users' CSI, but not their data traffics. Users are assumed to be independent and randomly distributed within a cell, and in each time slot, one active user is served by each BS.

First, we define the precoded signal vector $\mathbf{x}_n = \mathbf{w}_n u_n \in \mathbb{C}^{N_t \times 1}$ at BS $n$, where $\mathbf{w}_n \in \mathbb{C}^{N_t \times 1}$ and $u_n$ represent the BF vector with $\|\mathbf{w}_n\|^2 \leq 1$ and the complex-valued data symbol with $\mathbb{E}[|u_n|^2] = 1$ for the $n$-th BS, respectively. Throughout the paper, we indicate the $k$-th user in cell $n$ as user $k_n$. Then,

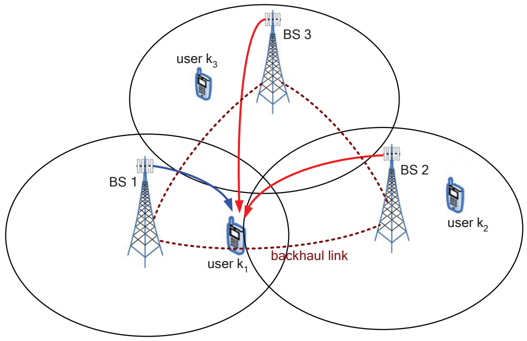



Fig. 1. A three-cell network MIMO system model

the received signal of user $k_n$, denoted as $y^{k_n}$, is given by

$$y^{k_n} = \sqrt{\alpha_n^{k_n}}(\mathbf{h}_n^{k_n})^H \mathbf{x}_n + \sum_{j=1, j\neq n}^{M} \sqrt{\alpha_j^{k_n}}(\mathbf{h}_j^{k_n})^H \mathbf{x}_j + z^{k_n} \quad (1)$$

where $\mathbf{h}_j^{k_n}$ is the channel response of user $k_n$ from BS $j$ whose entries are independent and identically distributed (i.i.d.) complex Gaussian with $\mathcal{CN}(0,1)$, and $z^{k_n}$ is the additive white Gaussian noise (AWGN) with $\mathcal{CN}(0,1)$. Also, $\alpha_j^{k_n}$ stands for the received power at user $k_n$ from BS $j$ determined by the distance dependent pathloss model $\alpha_j^{k_n} = \alpha_0 \big(d_0/d_j^{k_n}\big)^\beta$ where $d_j^{k_n}$ denotes the distance from BS $j$ to user $k_n$, and $\alpha_0$ is the received power at the reference distance $d_0$ and $\beta$ equals the pathloss exponent. We assume the individual per-BS power constraint since the BSs are not collocated. Also, we assume that user $k_n$ has perfect knowledge of its local CSI $\{\mathbf{h}_j^{k_n}\}_{j=1}^M$, i.e., the channel vectors connected to itself.

Under the single user detection at the receiver, the individual rate $R^{k_n}$ of user $k_n$ can be represented from (1) as

$$R^{k_n} = \log_2\left(1 + \text{SINR}^{k_n}\right) \quad (2)$$

where $\text{SINR}^{k_n}$ is the received SINR of user $k_n$ given by

$$\text{SINR}^{k_n} = \frac{\alpha_n^{k_n}\left|(\mathbf{h}_n^{k_n})^H \mathbf{w}_i\right|^2}{1 + \sum_{j=1, j\neq n}^{M} \alpha_j^{k_n}\left|(\mathbf{h}_j^{k_n})^H \mathbf{w}_j\right|^2}.$$

In this paper, our purpose is to maximize the weighted sum rate (WSR) performance under some fairness considerations for users. By denoting the set of $M$ users selected by BSs as $\mathcal{K} = \{k_1, \cdots, k_M\}$, the WSR $R_w(\mathcal{K})$ can be defined as

$$R_w(\mathcal{K}) = \sum_{n=1}^{M} w^{k_n} R^{k_n} \quad (3)$$

where the weight coefficient $w^{k_n}$ is determined by the required quality of service depending on applications.

## III. Adaptive Inter-Cell Interference Cancellation

In this section, we review the concept of adaptive ICIC techniques proposed in [11], where only a single user was assumed per BS. Then, we formulate the objective of our design for systems having multiple users in a cell as described in Section II. Throughout the paper, $M \leq N_t$ is assumed, where we do not have to apply power control, i.e., $\|\mathbf{w}_n\|^2 = 1$, according to the proof provided in [8, Proposition 1].

The principle idea of the adaptive ICIC is to decide whether it is better to apply interference cancellation or simply perform distributed single-cell BF. Depending on users' fading channel states and locations, each BS can choose its BF strategy, denoted by $s_n$, between the following two schemes based on the local CSI knowledge [11].

1) Maximum ratio transmission (MRT): The MRT is the optimal strategy for the single-cell MISO channels which maximizes the received signal power, given by $\mathbf{w}_n^{\text{MRT}} = \mathbf{h}_n^{k_n}/\|\mathbf{h}_n^{k_n}\|$.
2) ZFBF: The ZFBF cancels interference to the neighboring BSs, while also maximizing the desired signal power. This becomes projection of $\mathbf{h}_n^{k_n}$ to the nullspace of $\mathbf{G}^{k_n} = [\mathbf{h}_n^{k_1} \cdots \mathbf{h}_n^{k_{n-1}} \ \mathbf{h}_n^{k_{n+1}} \cdots \mathbf{h}_n^{k_M}]$, given by

$$\mathbf{w}_n^{\text{ZF}} = \frac{\left(\mathbf{I}_{N_t} - \mathbf{G}^{k_n}\left((\mathbf{G}^{k_n})^H\mathbf{G}^{k_n}\right)^{-1}(\mathbf{G}^{k_n})^H\right)\mathbf{h}_n^{k_n}}{\left\|\left(\mathbf{I}_{N_t} - \mathbf{G}^{k_n}\left((\mathbf{G}^{k_n})^H\mathbf{G}^{k_n}\right)^{-1}(\mathbf{G}^{k_n})^H\right)\mathbf{h}_n^{k_n}\right\|}.$$

It was shown in [8] that for the $M = 2$ case, any point of the Pareto boundary of the MISO interference channel can be achieved by linear combinations of MRT and ZFBF. However, the optimal choice of the "selfishness" parameter $\lambda_n, \ \forall n$ which maximizes the WSR was not addressed. On the contrary, the authors in [11] suggest a simple adaptive switching scheme between the above two strategies, which not only makes the beamformer design easier but also offers comparable performance from a selection gain.

On the other hand, one aspect not addressed in [11] is the issue of inter-cell user scheduling. When multiple users exist in a cell as in (1), finding the best strategy set $\mathcal{S} = \{s_1, \cdots, s_M\}$ gets coupled with the joint user selection process. Thus, our objective becomes much more complicated since we have to jointly choose the user set $\hat{\mathcal{K}} = \{\hat{k}_n\}_{n=1}^M$ and the strategy set $\hat{\mathcal{S}} = \{\hat{s}_n\}_{n=1}^M$ in order to maximize the WSR. We can mathematically formulate this problem as

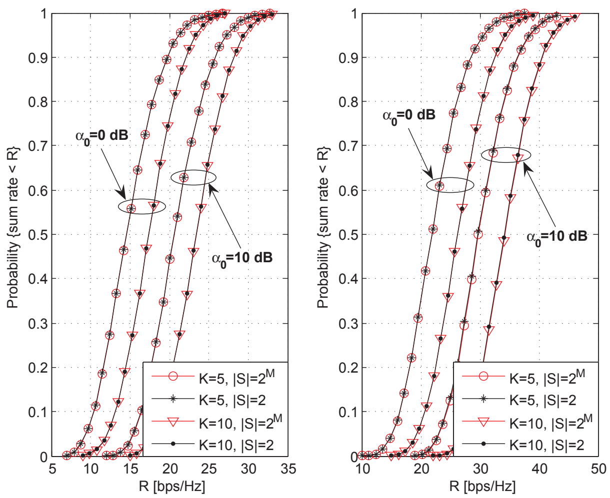
$$(\hat{\mathcal{K}}, \hat{\mathcal{S}}) = \arg\max_{\mathcal{K},\,\mathcal{S}} R_w(\mathcal{K}, \mathcal{S}) = \arg\max_{\mathcal{K},\,\mathcal{S}} \sum_{n=1}^{M} w^{k_n} R^{k_n}(\mathcal{S}) \quad (4)$$

where $R_w(\mathcal{K}, \mathcal{S})$ and $R^{k_n}(\mathcal{S})$ correspond to $R_w(\mathcal{K})$ and $R^{k_n}$, respectively, when $\mathcal{S}$ is given.

Evidently, solving (4) in realistic systems causes two major problems. First, it requires exhaustive search having a complexity of $\mathcal{O}(2^M K^M)$, which becomes prohibitive as $K$ or $M$ grows large. Next, in order to compute $R_w(\mathcal{K}, \mathcal{S})$ for all $\mathcal{K} = \{k_n\}_{n=1}^M$, the BSs should share the global CSI of all users at every transmission, which increases the backhaul traffic. Although the scheme proposed in [11] adopts the ergodic sum rate $\mathbb{E}[R_w(\mathcal{K}, \mathcal{S})]$ up to $M = 3$ which does not require the exchange of instantaneous CSI, the closed-form equations for $\mathbb{E}[R_w(\mathcal{K}, \mathcal{S})]$ are even more complicated to compute than the instantaneous rate $R_w(\mathcal{K}, \mathcal{S})$.

## IV. Proposed Beamforming Strategy and User Selection Algorithm

Motivated by the previous discussion, we now investigate a new low complexity adaptive ICIC and user selection algorithm. As in [11], we only consider the two beamforming




(a) $M = 2$ cell

(b) $M = 3$ cell

Fig. 2. Comparison of outage probability for the sum rates between $|\mathcal{S}| = 2^M$ case and $|\mathcal{S}| = 2$ case

strategies, i.e., the MRT and the ZFBF. Other solutions such as signal-to-leakage-plus-noise ratio (SLNR) based beamforming [12] are not considered since their analysis is usually complicated and $s \in \{\text{MRT}, \text{ ZF}\}$ is sufficient to achieve good performance. We develop the following two-step procedure.

1) Phase I: Each user decides its preferred BF strategy using a threshold based on our expected SINR analysis, and feeds back its choice to the corresponding BS.
2) Phase II: Based on the feedback in Phase I, BSs jointly perform a successive user scheduling algorithm to find $(\hat{\mathcal{K}}, \hat{\mathcal{S}})$ whose search complexity is linear in $K$.

Before describing each stage in detail, we impose a useful assumption to the BF strategies $\mathcal{S} = \{s_n\}_{n=1}^M$. That is, all BSs utilize the same strategy $s$ at each time slot as

$$s \triangleq s_1 = s_2 = \cdots = s_M, \tag{5}$$

which means that we consider only two homogeneous cases $s = \text{MRT}$ and $s = \text{ZF}$ among total $2^M$ possible transmission modes. Thereby, our strategy set reduces to $\mathcal{S} = \{s\}$.

Nevertheless, a performance loss incurred by (5) is insignificant in our CS/CB system with a moderate number of users. Figure 2 compares the outage probability for the sum rate of two cases $|\mathcal{S}| = 2^M$ and $|\mathcal{S}| = 2$ in two-cell and three-cell systems with $N_t = 4$. The cell edge signal-to-noise ratio (SNR) is set to 0 and 10 dB, which is given as $\alpha_0$ with $d_0 = R$. Other basic settings are the same as in Section V. From the curves, we observe that considering only the $\mathcal{S} = \{s\}$ cases results in almost nosum rate performance loss. This is because even though the optimal solution $(\hat{\mathcal{K}}, \hat{\mathcal{S}})$ of (4) may have different strategies at different BSs, the coordinated scheduler can always find another suboptimal set $(\mathcal{K}, \mathcal{S})$ which satisfies $s_1 = \cdots = s_M$ and achieves almost the same performance. Similar results will be shown in Section V.

### *A. Phase I: User-Oriented Adaptive ICIC*

The Phase I process is applied independently at each user terminal. In this phase, user $k_n$ predetermines its preferred BF strategy, denoted by $s^{k_n}$, based on its local CSI, and feeds back its choice $s^{k_n}$ to BS $n$. Different from the coordinated strategy in [11], the best thing that each user can do is to choose $s^{k_n}$ which maximizes its individual rate $R^{k_n}$, or equivalently the received SINR.

Thanks to (5), this problem is simply written by considering only $s = \text{MRT}$ and $s = \text{ZF}$ cases as

$$s^{k_n} = \arg \max_{s \in \{\text{MRT, ZF}\}} \text{SINR}^{k_n}(s)$$

where $\text{SINR}^{k_n}(s)$ represents the SINR of user $k_n$ when the same strategy $s \in \{\text{MRT}, \text{ ZF}\}$ is applied at all BSs. However, the true values of $\text{SINR}^{k_n}(s)$ cannot be estimated at the receiver, since users do not know the BF vectors of neighboring BSs $\{\mathbf{w}_j^s\}_{j \neq n}$ and even its own beamformer $\mathbf{w}_n^{\text{ZF}}$ when $s = \text{ZF}$ is applied.

In this case, the *expected* SINR is a useful performance measure for each user. User $k_n$ will select the MRT if

$$\mathbb{E}[\text{SINR}^{k_n}(\text{MRT})] \geq \mathbb{E}[\text{SINR}^{k_n}(\text{ZF})], \tag{6}$$

and choose the ZFBF otherwise. Notice that the expectation in this work is only for the unknown BF vectors, not for all random variables.

Applying Jensen's inequality, the expected SINR of user $k_n$ for the MRT case with respect to $\{\mathbf{w}_j^{\text{MRT}}\}_{j \neq n}$ can be approximated as

$$\begin{aligned}\mathbb{E}[\text{SINR}^{k_n}(\text{MRT})] &\approx \frac{\alpha_n^{k_n} \left\|\mathbf{h}_n^{k_n}\right\|^2}{1 + \sum_{j \neq n} \alpha_j^{k_n} \left\|\mathbf{h}_j^{k_n}\right\|^2 \mathbb{E}\left[\left|(\tilde{\mathbf{h}}_j^{k_n})^H \mathbf{w}_j^{\text{MRT}}\right|^2\right]} \\ &= \frac{\alpha_n^{k_n} \left\|\mathbf{h}_n^{k_n}\right\|^2}{1 + \frac{1}{N_t} \sum_{j \neq n} \alpha_j^{k_n} \left\|\mathbf{h}_j^{k_n}\right\|^2}\end{aligned} \tag{7}$$

where $\tilde{\mathbf{h}}_j^{k_n} = \mathbf{h}_j^{k_n} / \left\|\mathbf{h}_j^{k_n}\right\|$. Here the last equality comes from the fact that $\mathbf{w}_j^{\text{MRT}}$ is chosen independently with $\tilde{\mathbf{h}}_j^{k_n}$ over $\mathbb{C}^{N_t}$ which makes $\left|(\tilde{\mathbf{h}}_j^{k_n})^H \mathbf{w}_j^{\text{MRT}}\right|^2$ beta distributed with parameters $(1, N_t - 1)$ [13].

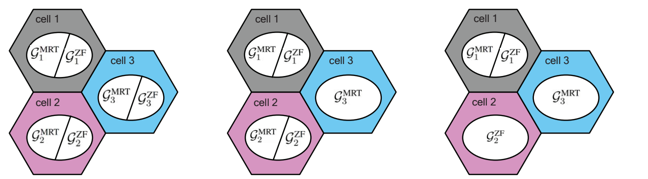
For the ZFBF case, the interference term is completely canceled out by $\{\mathbf{w}_j^{\text{ZF}}\}_{j \neq n}$ which yields

$$\mathbb{E}[\text{SINR}^{k_n}(\text{ZF})] = \alpha_n^{k_n} \left\|\mathbf{h}_n^{k_n}\right\|^2 \mathbb{E}\left[\left|(\tilde{\mathbf{h}}_n^{k_n})^H \mathbf{w}_n^{\text{ZF}}\right|^2\right]. \tag{8}$$

In order to calculate the expectation in (8) with respect to $\mathbf{w}_n^{\text{ZF}}$, we decompose $\tilde{\mathbf{h}}_n^{k_n}$ into two orthogonal components as $\tilde{\mathbf{h}}_n^{k_n} = \cos(\theta_n^{k_n})\mathbf{g}_n^{k_n} + \sin(\theta_n^{k_n})\mathbf{g}_n^{k_n \perp}$ where $\mathbf{g}_n^{k_n} \in \mathbb{C}^{N_t \times 1}$ and $\mathbf{g}_n^{k_n \perp} \in \mathbb{C}^{N_t \times 1}$ are arbitrary vectors which belong to the subspace spanned by $\{\mathbf{h}_n^{k(j)}\}_{j \neq n}$ and its nullspace, respectively, and $\theta_n^{k_n}$ denotes the angle between $\tilde{\mathbf{h}}_n^{k_n}$ and $\mathbf{g}_n^{k_n}$, i.e., $\cos\theta_n^{k_n} = \left|(\tilde{\mathbf{h}}_n^{k_n})^H \mathbf{g}_n^{k_n}\right|$. Then, since $\mathbf{g}_n^{k_n}$ is orthogonal to $\mathbf{w}_n^{\text{ZF}}$ and independent of $\theta_n^{k_n}$, it follows

$$\begin{aligned}\mathbb{E}\left[\left|(\tilde{\mathbf{h}}_n^{k_n})^H \mathbf{w}_n^{\text{ZF}}\right|^2\right] &= \mathbb{E}\left[\left|(\cos(\theta_n^{k_n})\mathbf{g}_n^{k_n} + \sin(\theta_n^{k_n})\mathbf{g}_n^{k_n \perp})^H \mathbf{w}_n^{\text{ZF}}\right|^2\right] \\ &= \mathbb{E}\left[\left|\sin\theta_n^{k_n} (\mathbf{g}_n^{k_n \perp})^H \mathbf{w}_n^{\text{ZF}}\right|^2\right] \\ &= \mathbb{E}\left[\sin^2\theta_n^{k_n}\right] \mathbb{E}\left[\left|(\mathbf{g}_n^{k_n \perp})^H \mathbf{w}_n^{\text{ZF}}\right|^2\right].\end{aligned} \tag{9}$$

In (9), $\theta_n^{k_n}$ is uniformly distributed in $[0, 2\pi]$ which results in $\mathbb{E}\left[\sin^2\theta_n^{k_n}\right] = \frac{1}{2}$. Also, because both $\mathbf{g}_n^{k_n \perp}$ and $\mathbf{w}_n^{\text{ZF}}$ are




(a) regular case (b) regular case ($|\hat{\mathcal{K}}^{\text{MRT}}| = 3$) (c) irregular case

Fig. 3. Examples of user classifications at BSs in the three-cell environment

i.i.d. vectors in the $(N_t - M + 1)$-dimensional nullspace of $\{\mathbf{h}_n^{k(j)}\}_{j \neq l}$, the term $\left|(\mathbf{g}_n^{k_n \perp})^H \mathbf{w}_n^{\text{ZF}}\right|^2$ is beta distributed with parameters $(1, N_t - M)$. Consequently, (8) can be solved as

$$\mathbb{E}[\text{SINR}^{k_n}(\text{ZF})] = \frac{\alpha_n^{k_n} \left\|\mathbf{h}_n^{k_n}\right\|^2}{2(N_t - M + 1)}. \tag{10}$$

Finally, comparing (7) and (10), the proposed criterion for choosing the MRT strategy in (6) can be simply obtained as

$$\sum_{j \neq n} \alpha_j^{k_n} \left\|\mathbf{h}_j^{k_n}\right\|^2 \leq N_t(2N_t - 2M + 1) \triangleq \Gamma(N_t, M). \tag{11}$$

Since $N_t \geq M$, the threshold $\Gamma(N_t, M)$ is always positive. Note that $\sum_{j \neq n} \alpha_j^{k_n} \left\|\mathbf{h}_j^{k_n}\right\|^2$ is the interference channel gain of user $k_n$ coming from neighboring BSs. This criterion states that if the interference power is strong, i.e., larger than $\Gamma(N_t, M)$, user $k_n$ prefers to be supported by ZFBF, together with other cell users who also want the ZFBF.

Thanks to the assumption $\mathcal{S} = \{s\}$ in (5), the proposed adaptation method (11) can be operated in a totally distributed manner. Only one more bit is required for each mobile in the feedback stage to deliver the choice of $s^{k_n}$ to its home BS.

### *B. Phase II: Successive Inter-Cell User Scheduling*

Now, since all users have already chosen their preferred strategy $s^{k_n}$, BS $n$ can classify users into two groups based on the users' feedback $s^{k_n}$. One is the MRT user group defined as $\mathcal{G}_n^{\text{MRT}}$ whose members have reported $s^{k_n} = \text{MRT}$, and the other is the ZFBF user group $\mathcal{G}_n^{\text{ZF}}$ which is a set of users who prefer $s^{k_n} = \text{ZF}$. The two sets are complementary, i.e., $\mathcal{G}_n^{\text{MRT}} \cup \mathcal{G}_n^{\text{ZF}} = \{1, \cdots, K\}$ and $\mathcal{G}_n^{\text{MRT}} \cap \mathcal{G}_n^{\text{ZF}} = \phi$. Then, we newly introduce two set notations $\mathcal{K}^{\text{MRT}}$ and $\mathcal{K}^{\text{ZF}}$ to replace $\mathcal{K} = \{k_n\}_{n=1}^M$, defined as $\mathcal{K}^{\text{MRT}} \triangleq \{k_n \in \mathcal{G}_n^{\text{MRT}}\}_{n=1}^M$ and $\mathcal{K}^{\text{ZF}} \triangleq \{k_n \in \mathcal{G}_n^{\text{ZF}}\}_{n=1}^M$

Normally, each BS has both two user groups, i.e., $\mathcal{G}_n^{\text{MRT}} \neq \phi$ and $\mathcal{G}_n^{\text{ZF}} \neq \phi$, as depicted in Figure 3 (a). However, there also exists a possibility that at least one BS has no user in one of two groups such as in Figure 3 (b) or (c). In Figure 3 (b), we can simply choose the MRT strategy to make sure that every cell serves one active user with not much performance loss. In contrast, in the case of Figure 3 (c), either cell 2 or cell 3 cannot be operated no matter which strategy is chosen under our assumption of (5). However, in the following lemma, we show that such an event hardly occurs unless $K$ is very small.

*Lemma 1:* For the $M$-cell case, the probability that both $\mathcal{G}_m^{\text{MRT}} = \phi$ and $\mathcal{G}_n^{\text{ZF}} = \phi$ occur for any $m$ and $n$ $(m \neq n)$ is upper bounded by $\binom{M}{2}\left(\frac{1}{4}\right)^K$.

*Proof:* By denoting $X \triangleq \sum_{j \neq n} \alpha_j^{k_n} \|\mathbf{h}_j^{k_n}\|^2$, the probability that user $k_n$ chooses the MRT is given from (11) by the CDF of $X$ as $F_X(\Gamma) = \Pr(X \leq \Gamma)$, where $\Gamma \triangleq \Gamma(N_t, M)$. Since the large and small scale fadings in $X$ are both i.i.d. over $k$ and $n$, it follows for given $m$ and $n$

$$\begin{aligned}\Pr\left(\mathcal{G}_m^{\text{MRT}} = \phi \text{ and } \mathcal{G}_n^{\text{ZF}} = \phi\right) &= \Pr(X \leq \Gamma)^K \Pr(X > \Gamma)^K \\ &= \left(F_X(\Gamma)\left(1 - F_X(\Gamma)\right)\right)^K \leq \left(\frac{1}{4}\right)^K\end{aligned}$$

where equality holds when $F_X(\Gamma) = \frac{1}{2}$. Since there are $\binom{M}{2}$ cases of choosing an $(m, n)$ pair among $M$ cells, we have Lemma 1. ■

According to Lemma 1, if $K = 20$ users exist in each of three cells for example, the probability that a certain BS does not operate is less than $3 \cdot 10^{-12}$ for all SNR range. Consequently, in our work, we neglect this probability and will consider only the regular cases shown in Figure 3 (a). The case of Figure 3 (b) can be done similarly.

Then, based on the user classification $\mathcal{G}_n^{\text{MRT}}$ and $\mathcal{G}_n^{\text{ZF}}$, we modify our original problem (4) as

$$(\hat{\mathcal{K}}, \hat{s}) = \begin{cases} (\hat{\mathcal{K}}^{\text{MRT}}, \text{MRT}), & \text{if } R_w(\hat{\mathcal{K}}^{\text{MRT}}, \text{MRT}) \geq R_w(\hat{\mathcal{K}}^{\text{ZF}}, \text{ZF}) \\ (\hat{\mathcal{K}}^{\text{ZF}}, \text{ZF}), & \text{otherwise,} \end{cases} \tag{12}$$

where $\hat{\mathcal{K}}^{\text{MRT}}$ and $\hat{\mathcal{K}}^{\text{ZF}}$ are determined by

$$\hat{\mathcal{K}}^{\text{MRT}} = \arg \max_{\mathcal{K}^{\text{MRT}}} R_w(\mathcal{K}^{\text{MRT}}, \text{MRT}) \tag{13}$$

$$\hat{\mathcal{K}}^{\text{ZF}} = \arg \max_{\mathcal{K}^{\text{ZF}}} R_w(\mathcal{K}^{\text{ZF}}, \text{ZF}). \tag{14}$$

From this modification, the two best sets $\hat{\mathcal{K}}^{\text{MRT}}$ and $\hat{\mathcal{K}}^{\text{ZF}}$ for each strategy are obtained separately by (13) and (14), and then their WSRs are compared to decide the final solution $(\hat{\mathcal{K}}, \hat{s})$. However, the overall search size of solving (13) and (14) is still $\mathcal{O}(K^M)$ in the worst case where all users in the network choose the identical strategy. Moreover, all users' global CSI still needs to be shared among BSs.

Thus, we seek an efficient heuristic algorithm to get solutions of (13) and (14). In order to reduce the search space, the proposed algorithm successively identifies each user of $\hat{\mathcal{K}}^{\text{MRT}} = \{\hat{k}_n^{\text{MRT}}\}_{n=1}^M$ and $\hat{\mathcal{K}}^{\text{ZF}} = \{\hat{k}_n^{\text{ZF}}\}_{n=1}^M$ at each BS. We approximate each user's individual rate using (7) and (10) as

$$\tilde{R}^{k_n}(s) \triangleq \log_2\left(1 + \mathbb{E}[\text{SINR}^{k_n}(s)]\right), \tag{15}$$

and also define the corresponding approximate WSR as

$$\tilde{R}_w(\mathcal{K}, s) \triangleq \sum_{n=1}^M w^{k_n} \tilde{R}^{k_n}(s). \tag{16}$$

Using these approximations, each procedure of finding $\hat{\mathcal{K}}^{\text{MRT}}$ and $\hat{\mathcal{K}}^{\text{ZF}}$ are described in Algorithms 1 and 2, respectively. We add some comments on Algorithms 1 and 2.

- Although the solutions $\hat{\mathcal{K}}^{\text{MRT}}$ and $\hat{\mathcal{K}}^{\text{ZF}}$ may depend on the scheduling order among $M$ cells, we do not consider this issue since the performance with a fixed order is good enough as will be shown in Section V.
- When computing (17) in Algorithm 1, we can do better than equation (7), since BS $n$ has knowledge of $\{\mathbf{w}_j^{\text{MRT}} = \tilde{\mathbf{h}}_j^{\hat{k}_j^{\text{MRT}}}\}_{j=1}^{n-1}$. Thus, the expectation for $\mathbb{E}[\text{SINR}^{k_i}(\text{MRT})]$

**Algorithm 1** Search procedure for $\hat{\mathcal{K}}^{\text{MRT}}$

1) **Cell $n (n = 1, \cdots, M-1)$:** In the increasing order of $n$, BS $n$ chooses its best MRT user $\hat{k}_n^{\text{MRT}}$ based on (16) and the information of predetermined users $\{\hat{k}_j^{\text{MRT}}\}_{j=1}^{n-1}$ as

$$\hat{k}_n^{\text{MRT}} = \arg \max_{k_n \in \mathcal{G}_n^{\text{MRT}}} \tilde{R}_w\big(\{\hat{k}_1^{\text{MRT}}, \cdots, \hat{k}_{n-1}^{\text{MRT}}, k_n\}, \text{MRT}\big), \quad (17)$$

and reports its index, weight $w^{\hat{k}_n^{\text{MRT}}}$ and the desired CSI $\alpha_n^{\hat{k}_n^{\text{MRT}}} \mathbf{h}_n^{\hat{k}_n^{\text{MRT}}}$ to BS $n+1, \cdots$, BS $M$.

2) **Cell $M$:** BS $M$ determines $\hat{k}_M^{\text{MRT}}$ based on the exact WSR (4) as

$$\hat{k}_M^{\text{MRT}} = \arg \max_{k_M \in \mathcal{G}_M^{\text{MRT}}} R_w\big(\{\hat{k}_1^{\text{MRT}}, \cdots, \hat{k}_{M-1}^{\text{MRT}}, k_M\}, \text{MRT}\big).$$

**Algorithm 2** Search procedure for $\hat{\mathcal{K}}^{\text{ZF}}$

1) **Cell $n (n = 1, \cdots, M-1)$:** BS $n$ independently chooses its best ZFBF user $\hat{k}_n^{\text{ZF}} \in \mathcal{G}_n^{\text{ZF}}$ which maximizes $w^{k_n}\tilde{R}^{k_n}(\text{ZF})$, and reports its index, weight $w^{\hat{k}_n^{\text{ZF}}}$ and the desired CSI $\alpha_n^{\hat{k}_n^{\text{ZF}}} \mathbf{h}_n^{\hat{k}_n^{\text{ZF}}}$ to BS $M$.

2) **Cell $M$:** BS $M$ obtains $\hat{k}_M^{\text{ZF}}$ based on the exact WSR as

$$\hat{k}_M^{\text{ZF}} = \arg \max_{k_M \in \mathcal{G}_M^{\text{ZF}}} R_w\big(\{\hat{k}_1^{\text{ZF}}, \cdots, \hat{k}_{M-1}^{\text{ZF}}, k_M\}, \text{ZF}\big).$$

$(i = 1, \cdots, n)$ can be performed with respect to $\{\mathbf{w}_j^{\text{MRT}}\}_{j=n+1}^{M}$, which yields

$$\mathbb{E}[\text{SINR}^{k_i}(\text{MRT})] \approx \frac{\alpha_i^{k_i}\|\mathbf{h}_i^{k_i}\|^2}{1+\sum_{j=1}^{i-1}\alpha_j^{k_i}|(\mathbf{h}_j^{k_i})^H\mathbf{w}_j^{\text{MRT}}|^2+\frac{1}{N_t}\sum_{j=i+1}^{M}\alpha_j^{k_i}\|\mathbf{h}_j^{k_i}\|^2}.$$

After going through Algorithms 1 and 2, we obtain $\hat{\mathcal{K}}^{\text{MRT}} = \{\hat{k}_n^{\text{MRT}}\}_{n=1}^{M}$ and $\hat{\mathcal{K}}^{\text{ZF}} = \{\hat{k}_n^{\text{ZF}}\}_{n=1}^{M}$. Then finally, by comparing $R_w(\hat{\mathcal{K}}^{\text{MRT}}, \text{MRT})$ and $R_w(\hat{\mathcal{K}}^{\text{ZF}}, \text{ZF})$ as in (12), we can determine the best user and the beamforming strategy set $(\hat{\mathcal{K}}, \hat{s})$.

Ultimately, the proposed scheme achieves our primary design goals. First, the inter-BS information overhead becomes smaller than that of the optimal case (4). Second, since the number of candidate users at each BS is $K$, the total search complexity required to carry out the successive scheduling in Phase II is only $\mathcal{O}(MK)$. Remember that the optimal problem (4) and the conventional scheme in [11] require joint exhaustive search scheduling with complexity $\mathcal{O}(2^M K^M)$.

## V. Simulation Results

In this section, we investigate the performance of multicell MISO downlink CS/CB systems employing the proposed adaptive ICIC and user selection algorithm. Both $M = 2$ and 3 cases are simulated with the cell radious $R = 0.5$ km. Users are randomly generated and dropped uniformly within the cell coverage. The pathloss exponent is set to $\beta = 3.75$. For small scale fadings, we employ spatially uncorrelated MIMO Rayleigh fading channels which are independently generated for each transmission.

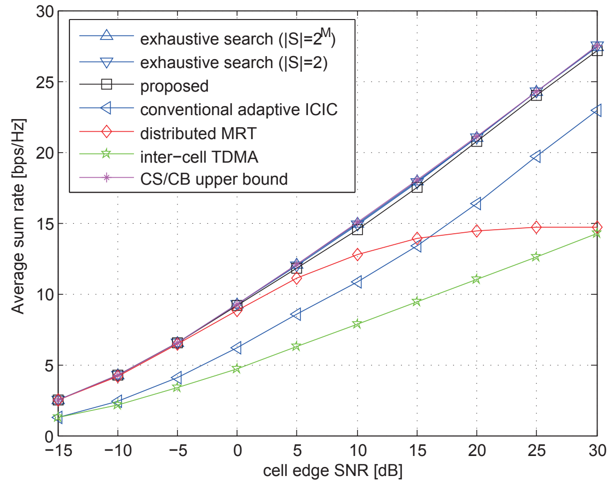



Fig. 4. Average sum rate performance of a two-cell network with $N_t = 2$ and $K = 30$

For users' weight calculation, we utilize the proportional fair scheduling, which provides a good trade-off between system throughput and fairness among users [14]. Thus, the weight $\omega^{k_n}$ for user $k_n$ is the reciprocal of its past average throughput $T^{k_n}$, which is updated in each time slot according to

$$T^{k_n}(t+1) = \begin{cases} \left(1-\frac{1}{t_c}\right)T^{k_n}(t) + \frac{1}{t_c}R^{k_n}(t), & \text{if } k_n = \hat{k}_n \text{ at } t \\ \left(1-\frac{1}{t_c}\right)T^{k_n}(t), & \text{otherwise} \end{cases}$$

where $t_c$ is a parameter which adjusts fairness. As a typical value, $t_c$ is set to $t_c = 100$.

For comparison with the proposed scheme (search size $\mathcal{O}(KM)$), the performance of the following CS/CB transmission strategies are evaluated.

- Optimal exhaustive search ($\mathcal{O}(2^M K^M)$): The *instantaneous* WSR is maximized according to exhaustive search of (4) over all possible $(\mathcal{K}, \mathcal{S})$.
- Reduced set exhaustive search ($\mathcal{O}(2K^M)$): From (5), $\mathcal{S}$ is restricted to only the cases $\mathcal{S} = \{\text{MRT}\}$ or $\{\text{ZF}\}$.
- Conventional adaptive ICIC ($\mathcal{O}(2^M K^M)$): The best set pair $(\hat{\mathcal{K}}, \hat{\mathcal{S}})$ is determined based on *ergodic* WSR comparison provided in [11].
- CS/CB upper bound ($\mathcal{O}(K^M)$): For the two-cell case, the system upper bound is established from the Pareto optimal solution [8] combined with exhaustive scheduling, where $0 \le \lambda_n \le 1$, $\forall n$ are found by $M$-dimensional joint search[1] with the global CSI knowledge.
- Inter-cell time-division multiple access (TDMA) ($\mathcal{O}(KM)$): Only one cell having the best user operates at each transmission.
- Distributed MRT ($\mathcal{O}(KM)$): A fully distributed strategy with the MRT and separate scheduling is compared.

Figure 4 presents the average sum rate of different schemes for two-cell systems with $N_t = 2$ and $K = 30$ users as a

[1]For $M \ge 3$, it is hard to find this solution since we should perform exhaustive search over $M(M-1)$ real and $M^2$ complex variables [8].

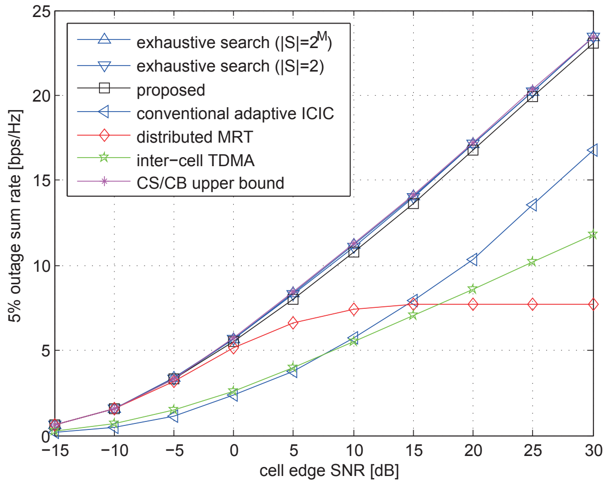



Fig. 5. 5% outage sum rate performance of a two-cell network with $N_t = 2$ and $K = 30$

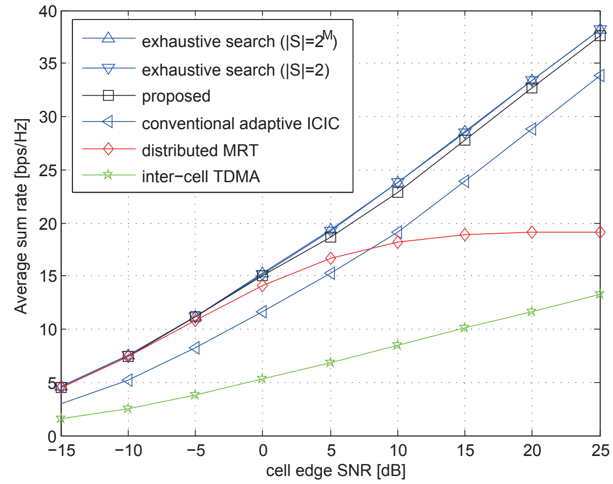



Fig. 6. Average sum rate performance of a three-cell network with $N_t = 4$ and $K = 20$

function of the cell edge received SNR. First, we compare two exhaustive results: the optimal scheme (4) with $\mathcal{S} = \{s_n\}_{n=1}^{M}$ and the suboptimal scheme with the reduced set $\mathcal{S} = \{s\}$. The two curves are shown to match almost perfectly, from which we can confirm again that our initial assumption (5) is performance lossless.

From the curves, we find that the proposed scheme achieves almost the same sum rate gains as the optimal one of the exhaustive search case. Moreover, it approaches the CS/CB sum rate upper bound. On the other hand, the conventional adaptive ICIC performs about 5 bps/Hz lower than the proposed scheme even though a user selection is made with exhaustive search. This is because $(\hat{\mathcal{K}}, \hat{\mathcal{S}})$ is determined according to the ergodic sum rate, which cannot capture the instantaneous link qualities of users.

In Figure 5, the 5% outage sum rate performance is presented in the same situation, which accounts for a cell edge sum rate gain. The link quality of cell edge users is more sensitive to the instant ICI power level, which is dominated by the channel directions of itself and neighboring users. However, the conventional adaptive ICIC and the distributed MRT do not consider the neighboring users' CSI, and thus their cell edge performance is shown to be severely degraded. In contrast, the proposed adaptive ICIC provides excellent performance also in this occasion for the whole SNR range.

Figure 6 depicts the average sum rates for the three-cell case with $N_t = 4$ and $K = 20$ users in each cell. A similar trend is observed with the two-cell case shown in Figure 4. In this case, the CS/CB upper bound is not drawn, since it is difficult to be found as explained earlier in this section.

## VI. Conclusions

In this paper, two design objectives for coordinated BF and coordinated inter-cell user scheduling have been investigated in multicell MISO downlink CS/CB systems. To avoid computationally expensive calculations of the joint optimal strategy, we have proposed a simple two-step adaptive ICIC technique which schedules the best users as well as the best BF strategy for each BS in terms of the WSR maximization. Simulations show that the proposed CS/CB scheme provides significant sum rate performance gains over conventional ones with only a linear increase in complexity with the number of users.

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