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# User Selection based on Inter-channel Interference for Massive MIMO under Line-of-sight Propagation

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## Abstract

Massive multiple-input multiple-output (MIMO) is seen as a key enabler for next-generation wireless communication systems. Increased throughput afforded by massive MIMO, however, may severely degrade when the number of users served by a single base station increases, calling for user scheduling algorithms. To deal with this problem, a new user selection algorithm, called inter-channel interference-based selection (ICIBS), is proposed. ICIBS drops those users that induce the highest interference to the remaining users. Simulations show that selecting users with ICIBS significantly improves the throughput, outperforming state-of-the-art user selection algorithms.

## 1 Introduction

Massive *multiple-input multiple-output* (MIMO) [1] systems employ a large number of antennas at the *base station* (BS), serving users within the same time-frequency radio resource. By using a large number of antennas, the small-scale fading effect can be eliminated through the so-called channel hardening, yielding a deterministic scalar channel [2]. Moreover, under favorable or asymptotically favorable propagation conditions, massive MIMO can achieve very high throughput by using linear processing [3]. These benefits make massive MIMO very attractive for wireless communication systems.

In practice, however, the *spectral efficiency* (SE) of massive MIMO systems may degrade severely when the number of users served by a single BS increases, mainly under *line-of-sight* (LoS) propagation. For example, the so-called favorable propagation requires the number of antennas to be much larger than the number of users [4], a condition that is unlikely to hold in crowded urban areas. In addition, the finite number of antennas at the BS limits the number of transmit beams that can be formed, thus constraining the number of users that can be served. Therefore, performing user scheduling, which includes *user selection* in its core, is of great importance for the proper operation of massive MIMO.

The SE of massive MIMO systems is directly related to the *signal-to-interference-plus-noise ratio* (SINR) associated with each user. Intuitively, users that cause strong interference among each other should not be transmitting simultaneously in order to maximize the overall SINR during a time slot. However, selecting users whose transmissions have the highest SINRs is computationally complex, requiring an exhaustive search across many possible combinations of users. Thus, several alternative solutions have been developed for conventional *multi-user* MIMO (MU-MIMO) systems, such as the *semi-orthogonal selection* (SOS) [5] and greedy-type algorithms [6, 7]. Other solutions for massive MIMO systems are the *random selection* (RS) [8] and the *correlation-based selection* (CBS) [9] approaches. The CBS algorithm selects users based on the correlation between pairs of users' channels, iteratively removing users that strongly interfere with one another. Hence, the CBS aims to maximize the SINR gain of a particular user and does not guarantee the best achievable overall SINR gain for the whole system.

In this paper, we propose a new user selection approach based on *inter-channel interference* (ICI), namely *ICI-based selection* (ICIBS). The proposal is inspired by CBS, and has similar computational complexity, however, it uses the average correlation between one channel and all the other users' channels in the cell. Hence, unlike CBS, ICIBS accounts for ICI in a global manner. We also derive the downlink SE bounds when maximum ratio transmission is used as precoder. Results show that using ICIBS yields an SE close to optimum, outperforming the competing algorithms.

## 2 Problem Formulation

### 2.1 System Model

Consider a single-cell massive MIMO system equipped with an $M$-antenna base station that serves $K$ single-antenna users, whose *uniformly random line-of-sight* (UR-LoS) MIMO channel is denoted by

$$\mathbf{G} = \mathbf{H}\mathsf{Diag}\left(\beta\right)^{1/2}, \tag{1}$$

where $\mathsf{Diag}\left(\beta\right)$ is a diagonal matrix with $\beta \in \mathbb{R}_{+}^{|\mathcal{K}|\times 1}$, the large-scale fading vector, on its main diagonal, $\mathbf{H} \in \mathbb{C}^{M\times|\mathcal{K}|}$

is the small-scale fading matrix, with

$$\mathbf{h}_k = e^{j\phi_k}\left[1 \quad e^{j\pi\sin(\theta_k)} \quad \cdots \quad e^{j(M-1)\pi\sin(\theta_k)}\right]^{\mathrm{T}}, \qquad (2)$$

$\phi_k \sim \mathcal{U}(-\pi,\, \pi)$ is the phase shift associated with the array and the $k$th user, $\theta_k \sim \mathcal{U}(-\pi,\, \pi)$ is the angle-of-arrival for the $k$th user, and $\mathcal{K} = \{1, 2, \cdots, K\}$ is the set of all user indexes, whose cardinality is $|\mathcal{K}| = K$.

For a downlink transmission with linear precoder and equal power allocation, the received signal can be expressed as

$$\mathbf{y} = \sqrt{\frac{\rho}{|\mathcal{K}|}}\, \mathbf{G}^{\mathrm{T}}\mathbf{W}\mathbf{s} + \mathbf{n}, \qquad (3)$$

where vector $\mathbf{y} \in \mathbb{C}^{|\mathcal{K}|\times 1}$ contains the signals received by the $|\mathcal{K}|$ users, $\rho \in \mathbb{R}_+$ is the downlink *signal-to-noise ratio* (SNR), $\mathbf{W} \in \mathbb{C}^{M\times|\mathcal{K}|}$ is the precoding matrix, $\mathbf{s} \in \mathbb{C}^{|\mathcal{K}|\times 1}$ is the vector of transmitted symbols whose covariance matrix is $\mathsf{E}\left\{\mathbf{s}\mathbf{s}^{\mathrm{H}}\right\} = \mathbf{I}_{|\mathcal{K}|}$, and the additive noise $\mathbf{n} \sim \mathcal{CN}\left(\mathbf{0}_{|\mathcal{K}|\times 1},\, \mathbf{I}_{|\mathcal{K}|}\right)$.

The downlink SE for (3) is given by [1]

$$R_{\mathrm{sum}} = \alpha \sum_{k\in\mathcal{K}} \log_2\left(1 + \gamma_k\right), \qquad (4)$$

where $\alpha \in \mathbb{R}_+$ is a constant that represents the ratio of the coherence time used for the downlink, the training time, and the coherence time, and $\gamma_k \in \mathbb{R}_+$ is the downlink SINR related to the $k$th user, which is given by [9]

$$\gamma_k = \frac{\rho\beta_k|\mathbf{h}_k^{\mathrm{T}}\mathbf{w}_k|^2}{|\mathcal{K}| + \rho\beta_k\sum_{k'\in\mathcal{K}\setminus\{k\}}|\mathbf{h}_k^{\mathrm{T}}\mathbf{w}_{k'}|^2},\ \forall k \in \mathcal{K}, \qquad (5)$$

where $\mathbf{h}_k$ and $\mathbf{w}_k$ are the $k$th column of matrices $\mathbf{H}$ and $\mathbf{W}$.

## 2.2 User Selection

Consider a case where $K$ is large enough to degrade massive MIMO transmissions. The BS should choose $L$ out of $K$ users to transmit and receive data in a given time slot. Mathematically, let $\mathcal{S} \subset \mathcal{K}$ be the set of selected users in a given time slot. Then, the optimization problem consists of finding $\mathcal{S}$, with $|\mathcal{S}| = L$, that maximizes the SE, i.e.,

$$\begin{aligned} &\underset{\mathcal{S}}{\text{maximize}}\ \alpha \sum_{k\in\mathcal{S}} \log_2\left(1+\gamma_k\right) \\ &\text{subject to } |\mathcal{S}| = L, \end{aligned} \qquad (6)$$

where the power is equally distributed among the $L$ selected users. *Note*: From now on, since the number of users sharing the radio resources simultaneously is $|\mathcal{S}|$, all equations and definitions in Section 2.1 must be adapted by simply replacing $\mathcal{K}$ with $\mathcal{S}$.

The user selection problem in (6) is not only non-convex, but also involves combinatorial optimization. In general, the optimal solution can only be found through an exhaustive search, which is impractical due to the high-dimensional search space in massive MIMO systems. This work proposes a new greedy/suboptimal algorithm to realize the user selection efficiently, avoiding the exhaustive search.

# 3 Inter-channel Interference-based Selection

An alternative approach to (6) is the state-of-the-art CBS algorithm [9], which uses the magnitude of the correlation coefficient between two users' channels defined as

$$r_{kk'} = \frac{|\mathbf{h}_k^{\mathrm{H}}\mathbf{h}_{k'}|}{\|\mathbf{h}_k\|_2\,\|\mathbf{h}_{k'}\|_2},\ \forall k, k' \in \mathcal{S},\ \ k \neq k'. \qquad (7)$$

The CBS is a greedy method that searches for a pair of users $(k, k')$ with the highest $r_{kk'}$ and removes the one with the highest magnitude correlation coefficient with the remaining users. From the SINR perspective, the CBS aims to maximize the SINR of one specific user, disregarding the SINR of the remaining users. It must be noted, however, that in some cases removing a user might inadvertently result in increased SINR of the remaining users. This is possible since the removed user may happen to have moderate magnitude correlation coefficients with the remaining users. Unlike CBS, which takes into account local (pair-wise) interference information, the proposed ICIBS considers the global interference. That is, at each iteration we find the user whose removal will lead to the highest overall SINR gain for the remaining/selected users. Thus, starting with set $\mathcal{S}_0 = \mathcal{K}$, we iteratively generate $\mathcal{S}_l \subset \mathcal{S}_{l-1}, l \in \mathbb{N}$, by removing the user that maximizes the ICI defined as

$$\psi_k^{(l)} = \frac{1}{|\mathcal{S}_{l-1}| - 1} \sum_{k'\in\mathcal{S}_{l-1}\setminus\{k\}} r_{kk'},\ \forall k \in \mathcal{S}_{l-1}. \qquad (8)$$

The algorithm stops at iteration $(K - L)$ since $|\mathcal{S}_{K-L}| = L$. The ICIBS method is summarized in Algorithm 1.

**Algorithm 1** ICIBS algorithm

**Require:** $L$ and $\mathbf{G}$
**Ensure:** $\mathcal{S}_0 = \mathcal{K}$
1: **for** $l = 1$ to $K - L$ **do**
2: $\quad\psi_k^{(l)} = \frac{1}{|\mathcal{S}_{l-1}|-1}\sum_{k'\in\mathcal{S}_{l-1}\setminus\{k\}} r_{kk'},\ \forall k \in \mathcal{S}_{l-1}$
3: $\quad k^* = \underset{k\in\mathcal{S}_{l-1}}{\operatorname{argmax}}\ \psi_k^{(l)}$
4: $\quad\mathcal{S}_l = \mathcal{S}_{l-1} \setminus \{k^*\}$
5: **end for**
6: **return** $\mathcal{S} = \mathcal{S}_{K-L}$

# 4 ICIBS with Maximum Ratio Transmission

The proposed ICIBS algorithm is independent of precoders used, however, for the MRT, we can show that the SE is upper and lower bounded by functions of the ICI. The MRT precoding vectors are given by:

$$\mathbf{w}_k = \frac{\mathbf{h}_k^*}{\|\mathbf{h}_k\|_2},\ \forall\, k \in \mathcal{S}, \qquad (9)$$

and the SINR is given by

$$\gamma_k = \frac{\rho\beta_k M}{|\mathcal{S}| + \rho\beta_k M\sum_{k'\in\mathcal{S}\setminus\{k\}} r_{kk'}^2},\ \forall k \in \mathcal{S}, \qquad (10)$$

since $\|\mathbf{h}_k\|_2 = \sqrt{M}$ for a UR-LoS channel. The following theorem addresses the downlink SE, assuming that all users' channels have the same large-scale fading.

*Theorem 4.1.* For a massive MIMO system with an $M$-antenna base station serving $L$ users with the same large-scale coefficient $\beta$, the downlink SE is bounded as follows:

$$\alpha \sum_{k \in \mathcal{S}} \log_2(1+\check{\gamma}_k) \leq R_{\text{sum}} \leq \alpha \sum_{k \in \mathcal{S}} \log_2(1+\tilde{\gamma}_k), \quad (11)$$

where

$$\check{\gamma}_k = \frac{\rho\beta M}{|\mathcal{S}| + \rho\beta M(|\mathcal{S}|-1)^2 \max\limits_{k\in\mathcal{S}} \psi_k^2}, \; \tilde{\gamma}_k = \frac{\rho\beta M}{|\mathcal{S}| + \rho\beta M(|\mathcal{S}|-1)\psi_k^2}. \quad (12)$$

*Proof.* The expressions for the ICI in (8) and downlink SINR in (10) can be rewritten, respectively, as

$$\psi_k = \frac{1}{|\mathcal{S}|-1}\|\mathbf{r}_k\|_1, \; \gamma_k = \frac{\rho\beta M}{|\mathcal{S}| + \rho\beta M \|\mathbf{r}_k\|_2^2}, \; \forall k \in \mathcal{S}, \quad (13)$$

where $\mathbf{r}_k \in \mathbb{R}_+^{(|\mathcal{S}|-1)\times 1}$ collects all correlations $r_{kk'}$, but $r_{kk}$.

Since $\frac{1}{|\mathcal{S}|-1}\|\mathbf{r}_k\|_1^2 \leq \|\mathbf{r}_k\|_2^2 \leq \|\mathbf{r}_k\|_1^2$ holds [10], then it follows from (13) that

$$(|\mathcal{S}|-1)\psi_k^2 \leq \|\mathbf{r}_k\|_2^2 \leq (|\mathcal{S}|-1)^2\psi_k^2 \leq (|\mathcal{S}|-1)^2 \max_{k\in\mathcal{S}} \psi_k^2.$$

Given (12), one therefore has $\check{\gamma}_k \leq \gamma_k \leq \tilde{\gamma}_k$, from which the bounds for the downlink SE in (11) follow. □

The inequalities in (11) show a direct relation between the ICI and the downlink SE with MRT. Therefore, by minimizing the maximum ICI, it is possible to improve the SE of the massive MIMO system, which is the main idea of the ICIBS approach.

## 5 Simulation Results

The performance of the proposed algorithm is assessed via numerical simulations by analyzing the effect of the number of selected users on the average throughput and the *cumulative distribution function* (CDF). The baseline state-of-the-art techniques for comparisons are the SOS [5] and the CBS [9]. The throughput has a linear relationship with the sum-spectral efficiency, which is given by $\mu = BR_{\text{sum}}$, where $B \in \mathbb{R}_+$ is the bandwidth in Hz. The choice for the throughput instead of the sum-spectral efficiency is due to the fact that the throughput measures the performance in *bits per second* (bps), which is a quality of service related to practical systems.

For the simulations, a 500-m radius hexagonal single-cell massive MIMO system with $M = 50$ and $K \in \{10, 75\}$ is used with $\alpha = 0.5$. The UR-LoS channel with a uniform linear antenna array and a bandwidth $B = 20$ MHz are used. The large-scale coefficient is known by the BS and given as

$$\beta_k = -148 - 37.6\log_{10}\left(\frac{d_k}{1\text{ km}}\right), \quad (14)$$

where $d_k \in \mathbb{R}_+$ is the distance between the $k$th user and the BS. Further, we consider the worst possible scenario in the cell, where all users are at the cell edge, yielding $\beta = -137$ dB for each user. Although this assumption seems restrictive at first glance, it facilitates to highlight the impact of small-scale fading on the system and how it can be compensated through user selection.

The radiated power at the BS is 10 W, the BS and user antenna gain is 0 dBi, and the noise figure for the users is 9 dB. Hence, the downlink SNR is 132 dB, yielding an effective SNR of $\bar{\rho} = \rho + \beta = -5$ dB. The SE is calculated using 5,000 realizations of the UR-LoS fading channel, and *maximum ratio transmitter* (MRT), *zero-forcing* (ZF), and *minimum mean squared error* (MMSE) precoders are used.

The throughput of massive MIMO systems is analyzed with perfect CSI knowledge. This setup deliberately aims to minimize the impact of the precoding algorithms to highlight the improvement brought about by user selection to the downlink throughput. Figure 1 depicts the average throughput *versus* the number of selected users for a massive MIMO system with $M = 50$. In this figure, the non-selection case is represented when $L = K$. As can be observed in Figure 1a, for $K = 10$, it is expected that the user selection would not provide any benefit for the system throughput since $M \gg K$. However, even in this case, the user selection can provide some improvement at the cost of dropping 2 users. Considering Figure 1b, the user selection has a huge impact on the throughput performance, being even more prevalent for ZF and MMSE precoders. In these figures, the ICIBS algorithm yields a slightly higher average throughput for ZF and MMSE precoders and similar average throughput as the CBS for the MRT when the optimum number of users is selected. It is worth highlighting that in Figure 1b, the user selection enables the use of ZF and MMSE precoders since they can only be used when $K < M$, which is already an advantage by itself.

Figure 2 shows the CDF of the throughput for $M = 50$, $K = 75$, and $L \in \{15, 38\}$. As it can be observed in Figure 2a, ICIBS outperforms both SOS and CBS for all precoders. The CBS has the worst performance for all precoders among all the user selection algorithms, whereas SOS performs slightly worse than ICIBS. Considering Figure 2b, there is no clear advantage among the algorithms and the performance is dependent on the precoding algorithm used. CBS achieves a slightly better performance with MRT precoder than the other algorithms, whereas SOS outperforms the others with ZF. The ICIBS yields improved throughput when compared to the other algorithms with the MMSE precoder.

## 6 Concluding Remarks

In this paper, a novel algorithm to perform user selection in massive MIMO systems based on the average interference among all users was proposed. The perfor-

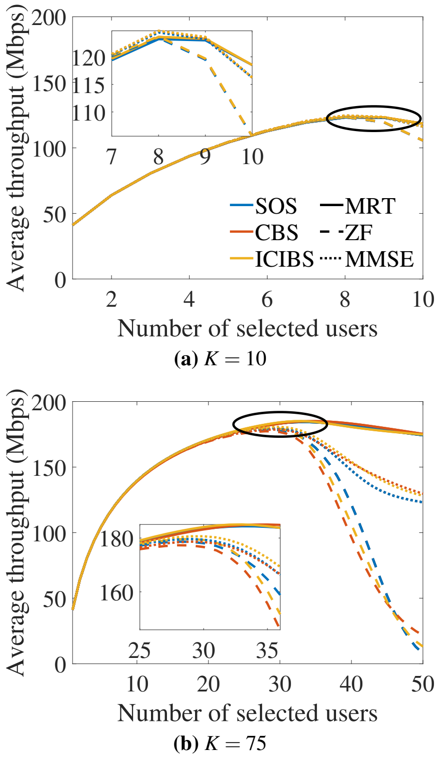


**Figure 1.** Average throughput *versus* the number of selected users for $M = 50$.

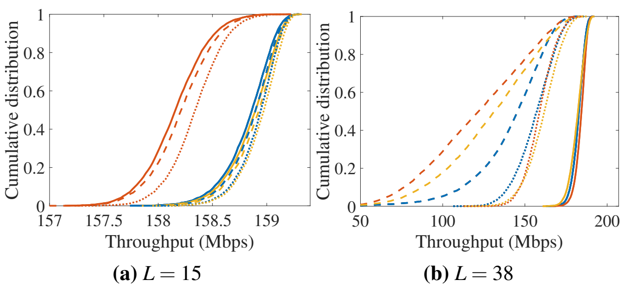


**Figure 2.** CDF of the sum-spectral efficiency for $M = 50$, $K = 75$, and $L \in \{15, 38\}$. The color and line specifications are the same ones used in Figure 1a.

mance of the proposed algorithm, ICIBS, was evaluated in a crowded scenario with results showing that it provides the best cost-effectiveness among the several user-selection schemes evaluated, outperforming the state-of-the-art. Future work will consider the performance of the ICIBS in different scenarios with more number of users and antennas, partial CSI knowledge, and explore how the power allocation can be combined with ICIBS to further improve performance.

## 7 Acknowledgements

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