Two-Layer Linear Processing for Uplink Massive MIMO Systems in the Presence of Co-Channel Interferers

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***Abstract*—Among linear combining methods, optimum combining (OC) provides optimal performance to reduce multipath fading effects and suppress interference, but it brings high computational complexity to bear in a massive multiple-input multiple-output (MIMO) scenario. To overcome this higher complexity, we propose in this paper a novel two-layer linear receiver processing scheme which can provide a range of complexity/performance trades offs. The proposed method consists of splitting the antenna array into a number of subsets, performing OC processing on each subset in a first processing layer, and then combining their respective outputs at a second layer, using either MRC or OC detectors. In the presence of co-channel interferers (CCI), we investigate the performance/complexity trade-off for the proposed receivers and we compare our methods with conventional receivers. The numerical simulations show that the proposed methods approach the performance of a conventional OC combiner, albeit with significantly reduced complexity.**

***Index Terms*—massive MIMO, two-layer receive processing, CCI, computational complexity.**

I. Introduction

Massive multiple-input multiple-output (MIMO) systems can theoretically achieve an orders of magnitude improvement in system throughput, degrees of freedom, or communication reliability [1], [2]. However, there are several challenges for designing large-scale antenna systems, including BS receiver signal processing complexity and inter-cell interference in a multi-cell environment [3]. Linear receivers have been widely studied in wireless communications for their low complexity. Typical linear receivers include maximal-ratio combining (MRC), zero-forcing (ZF) and minimum mean-square-error (MMSE). They are candidates for practical implementation of massive MIMO systems [1]. Several studies have investigated receiver-side array processing and the performance of massive MIMO systems from different perspectives [4], [5]. If the number of receive antennas grows to infinity, the effect of intra-cell interference and additive noise vanishes [1]. Also, simple coherent linear processing, such as MRC/eigenbeamforming, is sufficient to achieve these advantages. However, in practice, this is not so simple due to the cost and energy consumption of the large associated number of RF chains. In [5], the authors showed that in a realistic system setting, ZF and MMSE receivers can attain the same performance as the MRC combiner with far fewer antennas. Since ZF and MMSE normally require a matrix inversion operation, their computational complexity scales in proportion with the third power of the size of the desired active user population.

For multicellular massive MIMO system, the performance is limited by inter-cell interference, which causes pilot contamination [1]. There are several interference mitigation techniques for multi-cell, multi-user MIMO systems, such as maximum likelihood multiuser detection [6], cooperative and coordinated MIMO [7]. However, these techniques induce significant implementation complexity. Therefore, while linear receivers like conventional ZF or MMSE provide a reduction of the intra-cell interference at the cost of a large number of BS antennas, it was shown in [8], [9] that at high SNRs, inter-cell interference does not vanish when fixing the ratio between the number of BS antennas and the number of users.

In this paper, we consider the MMSE receiver according to two formulations. Firstly, the conventional single-cell MMSE (S-MMSE) receiver is examined based on the so-called MIMO formulation which relies only on channel estimates for intra-cell users to jointly detect the desired signals and ignores or treats the inter-cell interference as uncorrelated noise in computing the weight vectors [5], [10]. On the other hand, the multi-cell MMSE (M-MMSE) receiver exploits all channel realizations of the users in all cells [4]. This is referred to as optimum combining (OC) in this work. It is shown in [4] that in multi-cell scenarios, the inter-cell channels can be estimated without any additional pilot overhead.

The OC combiner is the most effective solution for multi-user systems [11], [12] since it explicitly takes into account both desired links for which channel state information (CSI) is readily available from the cell of interest (COI) and out-of-cell interfering links from the overlaid wireless communications systems. This, however, involves higher implementation complexity in computing the OC weights that scales in a polynomial fashion with the size of the antenna array [3]. These methods are of cubic computation complexity and are particularly difficult to perform in real-time massive MIMO systems. Therefore, given the large size of antenna arrays, finding an appealing trade-off point between system performance and complexity is of great interest. In this paper, we propose a low-complexity detector based on a two-layer linear receiver structure, which is computationally simpler than an OC detector and that scales better than an S-MMSE detector, while offering interference nulling roughly like OC. We investigate the performance of massive MIMO two-layer receive processing in the presence of CCI and compare the obtained performance with those of other conventional detectors.

II. System Model

Consider a massive MIMO system where the BS is equipped with L receive antennas and is servicing a population of M users with the same bandwidth. The number of antennas L is assumed to be at least an order of magnitude greater than M. The system operates in the presence of I unequal power CCI, which presumably originate from outside the COI, implying that their channels are unknown at the BS. Both the desired and the interfering users are assumed to undergo flat Rayleigh fading. Then, the received vector is

$$\mathbf{x} = \sqrt{P_0}\,\mathbf{H}\,\mathbf{s} + \mathbf{H}^{'}\,\mathbf{P}^{\frac{1}{2}}\,\mathbf{s}^{'} + \mathbf{n}, \tag{1}$$

where $\mathbf{H} \in \mathbb{C}^{L\times M}$ and $\mathbf{H}^{'} \in \mathbb{C}^{L\times I}$ are the channel matrices for the desired and interfering users, respectively. Provided that the interelement spacings at the BS are sufficiently large, the fading processes can be assumed uncorrelated across the array. The elements in $\mathbf{H}$ and $\mathbf{H}^{'}$ are assumed independent distributed complex Gaussian variables, i.e., $h_{lm} \sim \mathcal{CN}(0,1)$ and $h_{li}^{'} \sim \mathcal{CN}(0,1)$. The vectors $\mathbf{s}$ and $\mathbf{s}^{'}$ are the transmitted signals from the M desired users and the I interferers, respectively. The average received power of each desired user is P_0. Here, we assume that all desired users have the same received power. The matrix $\mathbf{P}$ is a diagonal matrix given by $[\mathbf{P}]_{ii} = P_i$ where P_i is the received power of the i-th interferer. Finally, $\mathbf{n} \sim \mathcal{CN}(0, \sigma_n^2\,\mathbf{I}_L)$ is the white Gaussian noise. In an uplink cellular environment, users within the same cell are power controlled by the same BS. For this reason, we assume that all desired users have equal receive power. However, the power control adjusts the power of the out-of-cell users at another BS. Hence, inter-cell interferers have unequal powers. We further assume that perfect CSI for all desired users is available at the BS receiver.

III. Linear Receivers

Given CSI knowledge, the desired signal can be extracted and the effect of interference mitigated by computing an appropriate set of combining coefficients or weights. The computation of said coefficients requires matrix inversion, which may be undesirable in a massive MIMO context due to the large size of the matrix to invert. The estimates of the desired signals are given by

$$\mathbf{z} = \mathbf{W}\,\mathbf{x}, \tag{2}$$

where $\mathbf{W} \in \mathbb{C}^{M\times L}$ is the weight combining matrix. The m-th row of $\mathbf{W}$, denoted $\mathbf{w}_m$, is the weight combining vector for the m-th user. From (2), the m-th element of $\mathbf{z}$, which is the estimate of s_m, is given by

$$\begin{aligned} z_m = \mathbf{w}_m\,\mathbf{x} = & \underbrace{\sqrt{P_0}\,\mathbf{w}_m\,\mathbf{h}_m\,s_m}_{\text{desired signal}} + \underbrace{\sum_{n\neq m}^{M}\sqrt{P_0}\,\mathbf{w}_m\,\mathbf{h}_n\,s_n}_{\text{intra-cell interference}} \\ & + \underbrace{\sum_{i=1}^{I}\sqrt{P_i}\,\mathbf{w}_m\,\mathbf{h}_i^{'}\,s_i^{'}}_{\text{inter-cell interference}} + \underbrace{\mathbf{w}_m\,\mathbf{n}}_{\text{noise}}. \end{aligned} \tag{3}$$

A. S-MMSE Receiver

The S-MMSE receiver minimizes the mean-square error under the assumption that the BS in the COI only has knowledge of intra-cell channel matrix $\mathbf{H}$. By treating the inter-cell interference term in (3) as uncorrelated noise, the S-MMSE receiver is given by

$$\mathbf{W}_{\text{S-MMSE}} = \left(\mathbf{H}^H\mathbf{H} + \frac{1}{P_0}\big(\sum_{i=1}^{I}P_i + \sigma_n^2\big)\,\mathbf{I}_M\right)^{-1}\mathbf{H}^H. \tag{4}$$

B. OC Receiver

In multi-cell scenarios, the OC technique explicitly tackles both multipath fading of the desired signals and the presence of CCI. Under the assumption that a BS can estimate all channel matrices of all, desired and interfering, users to further improve the performance, the vector corresponding to the optimal receive weights for user m is derived as [4]

$$\begin{aligned} \mathbf{w}_{OC,m} &= \left(P_0\,\mathbf{H}\,\mathbf{H}^H + \mathbf{H}^{'}\mathbf{P}\,\mathbf{H}^{'H} + \sigma_n^2\mathbf{I}_L\right)^{-1}\sqrt{P_0}\,\mathbf{h}_m, \\ &= \sqrt{P_0}\,\mathbf{R}_{xx}^{-1}\,\mathbf{h}_m, \end{aligned} \tag{5}$$

where $\mathbf{R}_{xx}$ is the covariance matrix for all desired signals at the different antenna elements. It has been shown in [11] that MMSE and OC receivers are equivalent with an arbitrary choice of a scaling factor.

C. Two-Layer Linear Processing

Given large-scale arrays of manageable sizes in practice, the above discussion highlights the need to develop algorithms that are computationally simpler than the OC receiver and that perform better than the S-MMSE receiver against inter-cell interference. Thus, in order to benefit from the interference mitigation capability of OC while maintaining moderate complexity, a modification in the reception scheme at the BS is put forward in this paper. Two-layer signal processing schemes have been studied for a single-user MIMO communication system in [13]–[15]. For massive MIMO systems, the two-layer detection method was proposed in a recent study in [16]. Since massive MIMO will be incorporated into mobile cellular networks, we will initially focus our attention on how to manage the interference created. The motivation behind this work is to improve the idea proposed in [16] and extend it for multi-cell massive MIMO systems in order to jointly detect M desired signals in the presence of I co-channel interferers. The proposed two-layer uplink processing scheme reception, as shown in Fig.1, consists of two stages: 1) dividing the large-scale array into a number of subsets of antennas, where each subset is of a given size N, and applying OC detection at the subset level; 2) combining the K resulting outputs using either MRC or OC detectors. We denote it as OC/MRC or OC/OC according to the processing at the second layer. With this architecture, all antennas in the array are equipped with an RF front-end and first-layer processing in each group is performed in the digital domain. The basic detection scheme is described as follows.

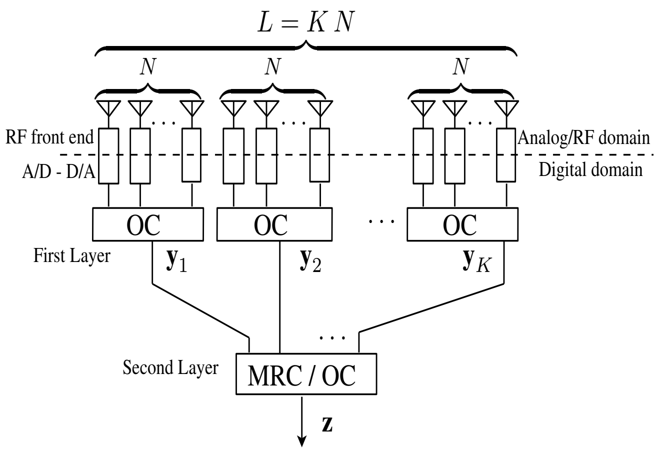


Fig. 1: Two-layer processing scheme for the uplink at the BS of a massive MIMO system

The first-layer subset processors implement OC in order to reduce interference. Thus, we have for all users

$$\mathbf{y}_k = \mathbf{W}_k\, \mathbf{x}_k, \qquad \text{for} \qquad k = 1, \ldots, K \tag{6}$$

where $\mathbf{y}_k = [y_{1k},\, y_{2k},\, \ldots,\, y_{Mk}]^T$, $\mathbf{x}_k \in \mathbb{C}^{N\times 1}$, and $\mathbf{W}_k \in \mathbb{C}^{M\times N}$ are the portion of $\mathbf{x}$ and the combining matrix corresponding to the k-th subset, respectively. Let $\mathbf{R}_{x_k}$ denote the covariance matrix of $\mathbf{x}_k$ given by

$$\mathbf{R}_{x_k} = P_0\, \mathbf{H}_k\, \mathbf{H}_k^H + \mathbf{H}_k^{'} \mathbf{P}\, \mathbf{H}_k^{'H} + \sigma_n^2 \mathbf{I}_N, \tag{7}$$

where $\mathbf{H}_k \in \mathbb{C}^{N\times M}$ and $\mathbf{H}_k^{'} \in \mathbb{C}^{N\times I}$ are the portion of $\mathbf{H}$ and $\mathbf{H}^{'}$ corresponding to the k-th subset, respectively. The m-th row of $\mathbf{W}_k$ can be computed as follows

$$\mathbf{w}_{mk} = \mathbf{w}_{OC,mk}^H = \sqrt{P_0}\, \mathbf{h}_{mk}^H\, \mathbf{R}_{x_k}^{-1}, \tag{8}$$

where $\mathbf{h}_{mk}$ is the m-th column of $\mathbf{H}_k$. As can be seen in (6) and (8), the output of the first layer processor for a given user m can be written as

$$\begin{aligned} y_{mk} = {} & \sqrt{P_0}\, \mathbf{w}_{mk}\, \mathbf{h}_{mk}\, s_m + \sqrt{P_0} \sum_{n\neq m}^{M} \mathbf{w}_{mk}\, \mathbf{h}_{nk}\, s_n \\ & + \sum_{i=1}^{I} \sqrt{P_i}\, \mathbf{w}_{mk}\, \mathbf{h}_{ik}^{'}\, s_i^{'} + \mathbf{w}_{mk}\, \mathbf{n}_k, \end{aligned} \tag{9}$$

where the first term in (9), denoted by $y_{d,mk}$, is the desired portion in the output of the first layer processor, while the remaining terms, denoted by $y_{I+N,mk}$, represent interference-plus-noise.

The second layer processor implements either MRC or OC detectors, depending on the choice of the subset size N compared to the number of intra-cell and inter-cell interferers. We clearly distinguish three cases:

1) Case 1: $N \leq M$. In this case, since more signals are taken into account when computing the OC weights, no degrees of freedom remain at the subset level to combat interference and multipath fading, and the system performance is interference-limited. It follows that there remains a certain amount of residual interference in the output of the first layer. Furthermore, this interference is dominated by the intra-cell interferers since their power is of the same order as the desired signal.

2) Case 2: $M \leq N \leq M + I$. In this case, the interference power of the users in the same cell is considerably reduced, even though there is still residual interference coming from other cells which is implicitly weaker. Hence, from this perspective, the performance is improved compared to the first case.

3) Case 3: $M + I \leq N$. In this case, more degrees of freedom are offered and the residual interference in the output of the first layer processors is significantly reduced. Therefore, the MRC becomes very efficient since it can achieve quasi-optimal performance. We propose herein to combine the K resulting outputs using MRC.

For the first and second cases where the performance of the receiver is limited by the effect of interference, it will be more efficient to apply the OC detector at the second layer as it allows for more efficient intra- and inter-cell interference suppression.

In order to apply either MRC or OC detectors at the second layer, we should find the expressions of the weighting matrix according to the result of first-layer processing. We denote the optimal weight vector for user m by $\mathbf{v}_m$. The input signal to the second layer is expressed as

$$\mathbf{y}_m = \left[\begin{array}{cccc} y_{m1} & y_{m2} & \ldots & y_{mK} \end{array}\right]^T = [y_{mk}]_{k=1\cdots K}^T, \tag{10}$$

where y_{mk} is given by (9). Therefore, the combined output at the second layer for user m is computed as

$$z_m = \mathbf{v}_m^H\, \mathbf{y}_m. \tag{11}$$

For the MRC detector at the second layer, the final output vector for user m may be expressed as

$$z_m = \sum_{k=1}^{K} v_{mk}^*\, y_{d,mk} + \sum_{k=1}^{K} v_{mk}^*\, y_{I+N,mk} \tag{12}$$

where v_{mk} is the optimal combining weight for user m on subset k. Hence, the combined SINR for user m is

$$\gamma_m = \frac{E\left[\left|\sum_{k=1}^{K} v_{mk}^*\, y_{d,mk}\right|^2\right]}{E\left[\left|\sum_{k=1}^{K} v_{mk}^*\, y_{I+N,mk}\right|^2\right]}, \tag{13}$$

$$= \frac{P_0 \left|\sum_{k=1}^{K} v_{mk}^*\, (\mathbf{h}_{mk}^H\, \mathbf{R}_{x_k}^{-1}\, \mathbf{h}_{mk})^2\, v_{mk}\right|}{\left|\sum_{k=1}^{K} v_{mk}^*\, \mathbf{h}_{mk}^H\, \mathbf{R}_{x_k}^{-1}\, \mathbf{R}_{I+N,k}\, \mathbf{R}_{x_k}^{-1}\, \mathbf{h}_{mk}\, v_{mk}\right|}, \tag{14}$$

$$
\mathbf{R}_{y_m} = \begin{bmatrix} P_0 \mathbf{h}_{m1}^H \mathbf{R}_{x_1}^{-1} \mathbf{h}_{m1} & P_0 \mathbf{h}_{m1}^H \mathbf{R}_{x_1}^{-1} \mathbf{R}_{x_1 x_2} \mathbf{R}_{x_2}^{-1} \mathbf{h}_{m2} & \dots & P_0 \mathbf{h}_{m1}^H \mathbf{R}_{x_1}^{-1} \mathbf{R}_{x_1 x_K} \mathbf{R}_{x_K}^{-1} \mathbf{h}_{mK} \\ P_0 \mathbf{h}_{m2}^H \mathbf{R}_{x_2}^{-1} \mathbf{R}_{x_2 x_1} \mathbf{R}_{x_1}^{-1} \mathbf{h}_{m1} & P_0 \mathbf{h}_{m2}^H \mathbf{R}_{x_2}^{-1} \mathbf{h}_{m2} & \dots & P_0 \mathbf{h}_{m2}^H \mathbf{R}_{x_2}^{-1} \mathbf{R}_{x_2 x_K} \mathbf{R}_{x_K}^{-1} \mathbf{h}_{mK} \\ \dots & \ddots & \dots & \dots \\ P_0 \mathbf{h}_{mK}^H \mathbf{R}_{x_K}^{-1} \mathbf{R}_{x_K x_1} \mathbf{R}_{x_1}^{-1} \mathbf{h}_{m1} & P_0 \mathbf{h}_{mK}^H \mathbf{R}_{x_K}^{-1} \mathbf{R}_{x_K x_2} \mathbf{R}_{x_2}^{-1} \mathbf{h}_{m2} & \dots & P_0 \mathbf{h}_{mK}^H \mathbf{R}_{x_K}^{-1} \mathbf{h}_{mK} \end{bmatrix} \quad (20)
$$

where $\mathbf{R}_{I+N,k}$ is the interference-plus-noise covariance matrix for the desired signal, which can be expressed using (7) as follows

$$
\mathbf{R}_{I+N,k} = \mathbf{R}_{x_k} - P_0 \mathbf{h}_{mk} \mathbf{h}_{mk}^H. \quad (15)
$$

We denote the expression $\mathbf{h}_{mk}^H \mathbf{R}_{x_k}^{-1} \mathbf{h}_{mk}$ by ρ_{mk}. Substituting (15) in (14), we obtain

$$
\gamma_m = \left| \frac{P_0 \sum_{k=1}^{K} v_{mk}^* \rho_{mk}^2 v_{mk}}{\sum_{k=1}^{K} v_{mk}^* \rho_{mk} v_{mk} - P_0 \sum_{k=1}^{K} v_{mk}^* \rho_{mk}^2 v_{mk}} \right| \quad (16)
$$

In order to maximize the output SINR, taking the conjugate derivative of (16) with respect to the weight vector v_{mk}, we obtain $\left| \sum_{k=1}^{K} \rho_{mk}^2 v_{mk} \right| \left| \sum_{k=1}^{K} v_{mk}^* \rho_{mk} v_{mk} \right| - \left| \sum_{k=1}^{K} \rho_{mk} v_{mk} \right| \left| \sum_{k=1}^{K} v_{mk}^* \rho_{mk}^2 v_{mk} \right| = 0$.
By using the Cauchy-Schwarz inequality, we have

$$
\left| \sum_{k=1}^{K} v_{mk}^* \rho_{mk} v_{mk} \right| \le \sum_{k=1}^{K} \left| v_{mk} \right|^2 \sum_{k=1}^{K} \left| \rho_{mk} \right| \quad (17)
$$

with equality achieved when $v_{mk}^* = \alpha \sqrt{\rho_{mk}}$, for $\alpha \neq 0$. Therefore, the optimal weight for MRC is

$$
v_{MRC,mk}^* = v_{mk}^* = \sqrt{\mathbf{h}_{mk}^H \mathbf{R}_{x_k}^{-1} \mathbf{h}_{mk}}. \quad (18)
$$

For the OC detector at the second layer, the optimal weight vector for user m is

$$
\mathbf{v}_{OC,mk} = \mathbf{R}_{y_m}^{-1} \mathbf{d}_m, \quad (19)
$$

where $\mathbf{R}_{y_m} \triangleq E[\mathbf{y}_m \mathbf{y}_m^H] \in \mathbb{C}^{K \times K}$ is the covariance matrix of the resulting signal of first-layer processing, and is computed as shown in (20) on top of this page. Moreover, by using (8) and (9), the channel vector $\mathbf{d}_m$ for user m is expressed as

$$
\mathbf{d}_m = \begin{bmatrix} P_0 \mathbf{h}_{m1}^H \mathbf{R}_{x_1 x_1}^{-1} \mathbf{h}_{m1} \\ \dots \\ P_0 \mathbf{h}_{mK}^H \mathbf{R}_{x_K x_K}^{-1} \mathbf{h}_{mK} \end{bmatrix} \quad (21)
$$

Therefore, it follows that the final output of the two-layer processor for M desired users is given by

$$
\mathbf{z} = \begin{bmatrix} \mathbf{v}_1^H \mathbf{y}_1 & \dots & \mathbf{v}_M^H \mathbf{y}_M \end{bmatrix}^T = \left[\mathbf{v}_m^H \mathbf{y}_m \right]_{m=1 \cdots M}^T, \quad (22)
$$

where

$$
\mathbf{v}_m^H = \begin{cases} \mathbf{v}_{MRC,m}^H = \left[\mathbf{v}_{mk}^H \right]_{k=1 \dots K}, & \text{for MRC,} \\ \mathbf{v}_{OC,m}^H = \mathbf{d}_m^H \mathbf{R}_{y_m}^{-1}, & \text{for OC.} \end{cases} \quad (23)
$$

IV. Computational Complexity analysis

The complexity of calculating all receive weights is summarized in Table I, which is evaluated in terms of the number of complex arithmetic operations multiplications and additions. It can be seen from (4), (5), (8) and (19) that all four methods involve matrix inversion operation. Hence, the computation complexity is dominated by this operation. Under the assumption that $M \ll L = K \times N$, we can conclude from Table I that the asymptotic complexity scaling is $\mathcal{O}(LM^2)$ for the S-MMSE receiver and $\mathcal{O}(L^3)$ for the OC receiver. The S-MMSE receiver has a computational complexity smaller than that of the OC receiver, but it does not explicitly deal with the CCI. Compared to the OC receiver, the proposed two-layer receiver OC/MRC can reduce the computational complexity from $\mathcal{O}(L^3)$ to $\mathcal{O}(KN^3)$. In order to further improve the performance of the OC/MRC receiver when the subset size N is smaller than all users, i.e. $N < M + I$, the second layer processor implements OC detection, which requires additional complexity in the order of $\mathcal{O}(MK^3)$. Therefore, the computational complexity is significantly reduced for the proposed receivers, especially when the subset size N is small.

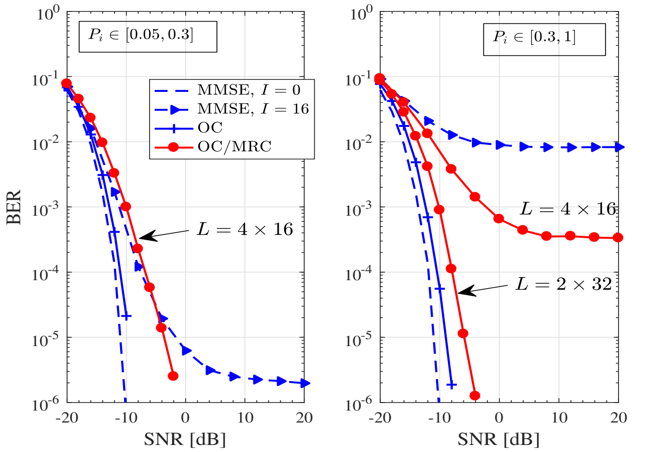
TABLE I: Complexity calculations

Technique	**Complexity**
MMSE	$M^3 + (3L + \frac{1}{2})M^2 + (2L - \frac{1}{2})M + I + 2$
OC	$L^3 + (3M + I + 1)L^2 + (2I + 3M)L - M + 2$
OC/MRC	$K \left[N^3 + (\frac{9}{2}M + I + 1)N^2 + (2I + \frac{9}{2}M)N + 2 \right] - M$
OC/OC	$K \left[N^3 + (3M + I + 1)N^2 + (2I + 3M)N - 2M + 2 \right]$ $+M \left[K^3 + (\frac{3}{2}N + 2)K^2 \right]$

V. Numerical Results

In this section, we investigate the performance of massive MIMO systems in the presence of unequal power CCI sources in terms of bit error rate (BER). All the results are obtained for quadrature amplitude (QAM) modulation. As a typical massive MIMO scenario, it is assumed for all curves that the number of interferer signals is twice the number of desired signals, i.e. $I = 2M$. We further assume that the desired signal set is of equal power 1. Due to power control and shadowing, the inter-cell users could impinge on the BS of interest with nearly the same power as desired signals, $P_i \in [0, 1]$.

Fig. 2 compares the performance of the proposed processing OC/MRC with the conventional S-MMSE and OC receivers, while considering two instances based on a subset size of



(a) (b)

Fig. 2: BER versus SNR for OC, S-MMSE and two-layer OC/MRC receivers for $L = 64$, $M = 8$ and $I = 16$: (a) weak out-of-cell interferers, $P_i \in [0.05, 0.3]$ (b) strong out-of-cell interferers $P_i \in [0.3, 1]$.

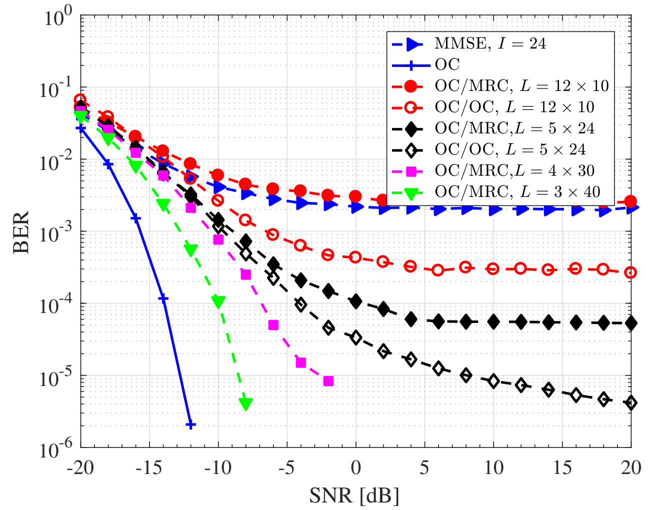


Fig. 3: BER versus SNR for OC, S-MMSE and proposed processing schemes OC/MRC and OC/OC for $L = 120$, $M = 12$ and $I = 24$ given $P = 0.55$

$N = 16$ and $N = 32$. The ideal case (without the presence of interferers, $I = 0$) is shown as a reference. In Fig. 2a, we consider the case of $I = 16$ weak out-of-cell interfering signals where the relative power varies between 0.05 (13 dB below desired users) to 0.3 (-5 dB). The optimal performance is obtained by OC detection at the cost of a higher complexity of $\mathcal{O}(64^3)$. This complexity can be reduced to $\mathcal{O}(4 \times 16^3)$ for the proposed scheme. However, an important observation is that S-MMSE receiver can achieve near-optimal BER performance with reduced complexity of order $\mathcal{O}(64 \times 8^2)$. Here, the total interference is small as there are fewer, weaker users. In this context, S-MMSE reception is sufficient to maintain good performance.

In Fig. 2b, we consider the case of strong out-of-cell interferers as in typical massive MIMO configurations where the power varies between 0.3 (-5 dB) and 1 (0 dB), e.g. $\bar{P} = \frac{1}{I}\sum_{i=1}^{I} P_i = 0.55$. We observe clearly that the performance of the S-MMSE receiver degrades severely as the SNR value increases. The BER performance saturates to a non-zero error floor due to stronger inter-cell interference. Since this interference has been taken into account while designing the proposed detector OC/MRC, the effect of other interfering users can be significantly reduced, especially when the subset size N is greater than all users, i.e. $N > M + I$. We see that when the 64-antenna array is divided into 2 sets of 32, the performance penalty is 2 dB while the complexity is reduced by a factor of $2^3/2 = 4$, while with 4 subsets of 16 the performance penalty grows to 8 dB (at a BER of 10^{-3}) but at a much reduced complexity by a factor of ($4^3/4 = 16$). As expected, the performance in the latter scenario ($N = 16$) presents an error floor at high SNR due to the residual interference in the output of the first layer processors.

Fig. 3 shows a different scenario with $M = 12$, $I = 24$ where the array size has been increased to $L = 120$ with various subset size $N = \{10, 24, 30, 40\}$. It is clear that for the S-MMSE receiver, there is still an error floor, even for larger array sizes, due to the residual out-of-cell interference. The OC scheme always achieves the best performance since it suppresses all interference, but at the cost of a huge complexity of order $\mathcal{O}(120^3)$. For comparison, we also depict in Fig. 3 several instances of our proposed schemes based on various subset sizes. Firstly, it is easy to see that in the extreme case where $N = 40 > M + I$, the proposed OC/MRC receiver provides a performance comparable to that of the OC receiver, in addition to being less complex. It reduces complexity from $\mathcal{O}(120^3)$ to $\mathcal{O}(3 \times 40^3)$, by a factor of $3^3/3 = 9$. This improvement mainly stems from the availability of more degrees of freedom at the first layer that allows for a significant reduction of both intra- and inter-cell interference. Secondly, where $M < N = \{24, 30\} < M + I$, the OC/MRC receiver achieves performance improvement when compared with the S-MMSE receiver. Comparing the two instances of OC/MRC corresponding to 5×24 and 3×40 at a BER of 10^{-3}, the performance penalty is 4 dB while the complexity is substantially reduced from $\mathcal{O}(3 \times 40^3)$ to $\mathcal{O}(5 \times 24^3)$. However, in the case where $N = 24$, the system is still limited by interference from other cells. Moreover, where $N = 10$ which represents the worst case in this study, the OC/MRC receiver does not perform well because insufficient degrees of freedom remain to combat interference. On the other hand, we observe that the second proposed scheme OC/OC improves considerably the performance compared to the OC/MRC where the subset size is inferior than the number of total users. We see that the BER floor is lowered, especially for the case where $N = 24$, at the cost of additional complexity of order $\mathcal{O}(12 \times 5^3)$. Furthermore, the OC/MRC curve corresponding to $L = 120 = 4 \times 30$ achieves a BER of 10^{-4} at an SNR of -7 dB with a computational complexity of $\mathcal{O}(4 \times 30^3)$. The same level of performance can be attained with an OC/OC receiver at an SNR of -4 dB with a somewhat smaller subset size ($L = 5 \times 24$) and a reduced complexity of $\mathcal{O}(24^3) + \mathcal{O}(12 \times 5^3)$. Therefore, it is interesting to note that using OC detector at the second layer has even greater benefits to achieve good performance while reducing complexity compared to the scenario where N is sufficiently large.

VI. Conclusion

In this paper, we have proposed low-complexity detectors based on a two-layer linear receiver structure for massive MIMO systems in the presence of unequal-power interferers. We have proved that the proposed schemes achieve a good trade-off between performance and complexity. Numerical results have shown that our methods outperform the S-MMSE receiver, and approach the performance of the OC receiver. We have also analyzed that the complexity of the proposed receiver is considerably lower than that of the OC receiver. When the interferers are considered weak, the performance of massive MIMO is not strongly affected, and hence we are particularly interested in the case when out-of-cell interferer power is large enough. Thus, the performance of massive MIMO is adversely affected given the rise of an error floor at high SNR. With the proposed schemes, performance can be enhanced by increasing the antenna array size or the number of subsets in the first layer, or both. In fact, the subset size N is a key parameter in achieving a desired performance/complexity tradeoff.

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