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Interference-aware MIMO precoder design with realistic power constraints

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***Abstract*—In this work an interference-aware precoder design is proposed for a downlink wireless cellular system. Each base-station designs a precoder with a joint MMSE-ZF criteria for the user information and the interference to other cells. In a realistic power constraint scenario, where each base-station has a limitation on the maximum power available power to be transmitted, the precoder filter can be analytically solved and this solution is provided. The simulated performance of the interference-aware filter in terms of achievable rates and MSE shows some advantages compared to other solutions in the literature designed with the aim of full interference cancellation such as block diagonalization schemes.**

I. INTRODUCTION

In wireless cellular systems, dealing with inter-cell interference is one of the main challenges for achieving the spectral efficiency requirements of future high capacity systems such as Long Term Evolution (LTE) and LTE-Advanced [1]. This is particularly noticeable when using universal frequency reuse as a strategy to avoid partitions on the spectral resources available. This scenario results in all cells within the system using all frequencies available and therefore severely interfering in the neighbouring cells. As this is a major problem, many strategies for mitigating the effect which interference has on the performance of the system are being proposed. Inter-cell interference (ICI) cancellation schemes have been proposed as an approach for improving both system throughput and cell-edge performance. State-of-the-art MIMO precoders based on Zero Forcing (ZF) formulations applicable to downlink multi-cell scenarios can be considered to be already well developed [2]. For instance, schemes that fully eliminate interference by means of block diagonalization (BD) of the channel matrix [3] are widely used today as they can be implemented analytically and allow uncoupling the precoder design from the power allocation problem. On the other hand, the literature seems to be lacking schemes based on minimum mean squared error (MMSE) criteria which can be applied to downlink multi-cell scenarios. This is mostly due to the difficulty of finding a closed form solution for the MMSE precoder when each base station (BS) has its own separate maximum transmitted power constraint. In this paper, we provide a joint MMSE-ZF precoder which allows to build precoders closer to MMSE schemes while still being solvable analytically in multi-cell scenarios.

Our proposal attempts to work around the aforementioned difficulty by formulating a simple interference-aware precoder design that lies in between full coordination between all base stations in the system (as it is assumed in BD schemes) and no coordination at all. Coordination is introduced by combining an intra-cell MMSE design with an inter-cell ZF based ICI cancellation scheme. To be precise, in our formulation each base BS works separately from others in the system to minimize, by using a ZF criteria, the interference caused by its transmission to other cells and to minimize the mean squared error (MSE) of the in-cell received signal. It should be noted that in order to be able to minimize the interference to other cells, our joint MMSE-ZF precoder requires that the BS knows the channel to all interfering users, but it does not need to know the interfering users data. Furthermore, since each BS computes its own precoder, we avoid having to solve an optimization problem with several power constraints yet we are able to introduce many of the benefits of coordination just by using knowledge of inter-cell channels. In a full coordination system such as those based on BD all BS work together to overcome interference and the precoder design needs information about the channel links from all BS to all users and besides needs to know all users data. In between a full coordination strategy and our strategy, we could choose to coordinate several BS in a clustering strategy and design a precoder that would need the user data of those BS that are working together. However, in this scenario, to work under realistic power constraints, each BS would need a different power constraint and, as it was mentioned before, the precoder can no longer be computed analytically because it would need numerical solving for the Lagrange multipliers.

To study and compare the performance of the proposed scheme, two signal-to-noise ratio (SNR) scenarios are addressed. In a low-SNR environment, noise drives the performance of the system and, therefore, it would be interesting to compare the performance of our scheme with other schemes in the literature with similar complexity that do not take into account interference such as those proposed in [4]. On the other hand, in a high-SNR environment, interference minimization is key for system performance and therefore our interference-aware filter is compared to schemes with full coordination that eliminate interference by means of block diagonalization of the channel matrix [3]. It is important to note that such BD strategy is significantly more costly given that all BS need knowledge of the data to be transmitted to all users in the system and also that a full receive filter matrix is needed in each of the receivers. In terms of the power allocation strategy needed for the BD, we will use a uniform power allocation to make a fair comparison with our proposal in terms of complexity for the allocation of power resources.

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There are other “interference-aware” strategy designs in the literature such as [5], [6], [7] which try to generalize point-to-point MIMO precoders by introducing some sort of ICI mitigation scheme in their original formulation. However, neither of those attempt to deal with the difficult MMSE formulation and use other cost functions as optimization criteria to design their precoders. For instance, [5] tries to maximize a magnitude they denote as signal-to-leakage-and-noise ratio (SLNR), [6] maximises the rate only considering MISO systems working in the high SNR regime, and [7] formulates a rather complex system model which includes full receive filters for each of the users and solves the per-BTS power allocation problem numerically, resulting in strong computational complexity. Other related papers are [8], where the authors propose a transmission scheme able to adaptively switch between interference-blind beamforming and a ZF-based interference cancellation scheme which, as our own work, assumes CSI knowledge but does not require base stations to have access to all user data. In the review process of this manuscript, one of the reviewers has pointed out the work in [9], a reference that we were not aware of. In this recent work, the authors propose a joint design of the transmitter and receiver in a multiuser cellular system, where the cost function for the precoder design also uses a zero forcing strategy for the out of cell interference, in that manuscript named leakage, and a MMSE strategy for the desired signal.

The rest of the paper is organized as follows. In section II the system model is defined. Section III formulates the optimization problem whose solution yields our interference aware precoder design. Sections IV and V provide simulation performance study and the conclusions.

Notations: Boldface letters represent vector or matrices and $\mathbf{I}_N$ is the $N \times N$ identity matrix. $\mathrm{Tr}\{\cdot\}$ and $\mathrm{blkdiag}\{\cdot\}$ are respectively the trace of a matrix and a block diagonal matrix. Hermitian and complex conjugate are noted by ^{H} and *.

II. SYSTEM MODEL

We assume a downlink channel in a wireless cellular system where for each of the L cells in the system, a precoder matrix is separately designed introducing awareness about the interference the BS is generating in the receivers belonging to other surrounding cells. Each BS is equipped with t antennas and is serving a user with r receive antennas, $K = r \leq t$ threads are intended for each user, thus the precoder matrix $\mathbf{W_{tx}} \in \mathbb{C}^{t \times r}$.

In this scenario, the channel matrix $\mathbf{H}$ takes into account the fading from the t antennas in the BS to the Lr receive antennas in the system. We can define a general partition for the channel matrix if we separate the r antennas from the user being served from the $a+b$ receive antennas outside the cell. The matrix corresponding to the $a+b$ receive antennas outside the cell is partitioned into two matrices to allow a more general notation given a fixed ordering of the stations. Thus, we have the following relation $(L-1)\,r = a+b$ and we can write the channel matrix as:

$$\mathbf{H} = \begin{pmatrix} \mathbf{H_{\bar{c},1}} \\ \mathbf{H_c} \\ \mathbf{H_{\bar{c},2}} \end{pmatrix} \tag{1}$$

where $\mathbf{H_{\bar{c},1}} \in \mathbb{C}^{a \times t}$, $\mathbf{H_{\bar{c},2}} \in \mathbb{C}^{b \times t}$, $\mathbf{H_c} \in \mathbb{C}^{r \times t}$ and thus $\mathbf{H} \in \mathbb{C}^{Lr \times t}$. In a practical scenario, we will easily have full access to the value of $\mathbf{H_c}$. However, it should be noted that having knowledge of $\mathbf{H_{\bar{c},1}}$ and $\mathbf{H_{\bar{c},2}}$ would require some sort of inter-cell channel estimation procedure, which may be costly. In some particular scenarios, such as urban environments, due to the high propagation loss, inter-cell interference is really severe only in the cell-boundaries. Thus, a realistic implementation could involve each BS knowing the channel to users in its neighbouring cells, and with that information, each cell could construct a partial estimate of the matrices $\mathbf{H_{\bar{c},1}}$ and $\mathbf{H_{\bar{c},2}}$ to apply the proposed method. In our specific study, we assume perfect $\mathbf{H}$ knowledge in each BS.

At the users side, we will assume a simple $\mathbf{W_{rx}}$ linear receiver. It should be noted that in this specific design, it only makes sense that this matrix affects the r receive antennas of the desired user since, by the lack of coordination, we do not have access to the value of other cell receivers. Furthermore, if we decide to use $\mathbf{W_{rx}} = \alpha \mathbf{I}_r$, this would be in fact an automatic gain control filter implemented with a scalar α, similarly to the one first introduced in [4]. Moreover, that gain can also be extended to the interference caused to other cells without loss of generality. In fact, the inclusion of the scaling factor serves as a mathematical trick which allows to solve the problem analytically, so that we can avoid resorting to numerical methods. With all that, we can rewrite the end-to-end signal model as:

$$\begin{pmatrix} \hat{\mathbf{u}}_{\bar{c},1} \\ \hat{\mathbf{u}}_c \\ \hat{\mathbf{u}}_{\bar{c},2} \end{pmatrix} = \alpha \begin{pmatrix} \mathbf{H_{\bar{c},1}} \\ \mathbf{H_c} \\ \mathbf{H_{\bar{c},2}} \end{pmatrix} \mathbf{W_{tx}} \mathbf{u} + \alpha \begin{pmatrix} \mathbf{n}_{\bar{c},1} \\ \mathbf{n}_c \\ \mathbf{n}_{\bar{c},2} \end{pmatrix} \tag{2}$$

where $\mathbf{u}, \hat{\mathbf{u}}_c, \mathbf{n}_c \in \mathbb{C}^r$, $\hat{\mathbf{u}}_{\bar{c},1}, \mathbf{n}_{\bar{c},1} \in \mathbb{C}^a$ and $\hat{\mathbf{u}}_{\bar{c},2}, \mathbf{n}_{\bar{c},2} \in \mathbb{C}^b$.

In the previous equation, $\hat{\mathbf{u}}_{\bar{c},1}$ and $\hat{\mathbf{u}}_{\bar{c},2}$ represent the interference generated by the transmission of $\mathbf{u}$ in the $a+b$ antennas outside the cell and $\hat{\mathbf{u}}_c \in \mathbb{C}^r$ is the estimate of the data symbols. We have also decomposed the noise vector $\mathbf{n}$ in three portions and we will assume that those three portions are uncorrelated and that the noise correlation matrix $\mathbf{R_n} = \mathrm{blkdiag}\left(\mathbf{R_n^{\bar{c},1}}, \quad \mathbf{R_n^c}, \quad \mathbf{R_n^{\bar{c},2}}\right)$.

A graphical representation of the current system model is depicted in Fig. 1. The new system model behaves as three different channels in parallel, all fed with the same signal vector $\mathbf{x} = \mathbf{W_{tx}}\mathbf{u}$. At the receiver side two of of the three received signal vectors which arise are undesired, i.e. interference, and their norms could be minimized.

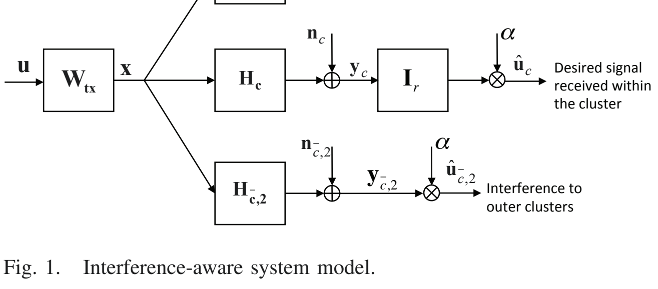

Fig. 1. Interference-aware system model.

III. INTERFERENCE-AWARE FILTER DESIGN

The optimization problem will still be cast as a minimum MSE (MMSE) problem. However, we will not only try to minimize the mean squared-error between $\hat{\mathbf{u}}_c$ and $\mathbf{u}$ but, also, we include the interference terms represented by $\hat{\mathbf{u}}_{\bar{c},1}$ and $\hat{\mathbf{u}}_{\bar{c},2}$ in the cost function and apply a ZF criteria to try to keep them as small as possible, leading to a joint MMSE-ZF design. Hence, the resulting optimization problem with a constraint on the total power transmitted by the BS becomes:

$$\min_{\mathbf{W_{tx}},\alpha} \mathbb{E}\left\{\left\|\begin{pmatrix}\mathbf{0}\\ \mathbf{u}\\ \mathbf{0}\end{pmatrix} - \begin{pmatrix}\hat{\mathbf{u}}_{\bar{c},1}\\ \hat{\mathbf{u}}_c\\ \hat{\mathbf{u}}_{\bar{c},2}\end{pmatrix}\right\|^2\right\} \quad s.t. \quad \mathbb{E}\left\{\|\mathbf{W_{tx}u}\|^2\right\} \leq P_{\max} \tag{3}$$

The Lagrangian for the optimization problem:

$$\begin{aligned}\mathcal{L}(\mathbf{W_{tx}},\alpha,\lambda) &= \mathrm{Tr}\left(\left(\mathbf{I}-\alpha\mathbf{H_c W_{tx}}\right)\mathbf{R_u}\left(\mathbf{I}-\alpha\mathbf{H_c W_{tx}}\right)^H\right)+\\ &+|\alpha|^2\,\mathrm{Tr}\left(\left(\mathbf{H_{\bar{c},1}W_{tx}}\right)\mathbf{R_u}\left(\mathbf{H_{\bar{c},1}W_{tx}}\right)^H\right)+\\ &+|\alpha|^2\,\mathrm{Tr}\left(\left(\mathbf{H_{\bar{c},2}W_{tx}}\right)\mathbf{R_u}\left(\mathbf{H_{\bar{c},2}W_{tx}}\right)^H\right)+\\ &+|\alpha|^2\,\mathrm{Tr}\left(\mathbf{R_n}\right)+\lambda\left(\mathrm{Tr}\left(\mathbf{W_{tx}R_uW_{tx}^H}\right)-P_{\max}\right)\end{aligned} \tag{4}$$

where $\mathbf{R_u}$ is the vector $\mathbf{u}$ correlation matrix. Differentiating with respect to $\mathbf{W}_{\mathbf{tx}}^H$:

$$\frac{\partial\mathcal{L}(\mathbf{W_{tx}},\alpha,\lambda)}{\partial\mathbf{W}_{\mathbf{tx}}^H} = |\alpha|^2\mathbf{H}^H\mathbf{H}\mathbf{W_{tx}R_u}+\lambda\mathbf{W_{tx}R_u}-\alpha^*\mathbf{H_c}^H\mathbf{R_u} \tag{5}$$

where the last equality comes from the definition of $\mathbf{H}$ done in equation (1). The final value for $\mathbf{W_{tx}}$ becomes:

$$\begin{aligned}\mathbf{W_{tx}} &= \alpha^*\left(|\alpha|^2\mathbf{H}^H\mathbf{H}+\lambda\mathbf{I}\right)^{-1}\mathbf{H_c}^H\\ &= \frac{\alpha^*}{|\alpha|^2}\left(\mathbf{H}^H\mathbf{H}+\frac{\lambda}{|\alpha|^2}\mathbf{I}\right)^{-1}\mathbf{H_c}^H\end{aligned} \tag{6}$$

It is very interesting to note that the solution obtained is not exactly an MMSE filter on the channel matrix $\mathbf{H}$: in the interference-aware formulation the matrix inverse is post-multiplied by $\mathbf{H_c}^H$ and not by the whole $\mathbf{H}^H$. Also, the fact that $\mathbf{H}_{\bar{\mathbf{c}},\mathbf{1}}^H\mathbf{H}_{\bar{\mathbf{c}},\mathbf{1}}$ and $\mathbf{H}_{\bar{\mathbf{c}},\mathbf{2}}^H\mathbf{H}_{\bar{\mathbf{c}},\mathbf{2}}$ are included within the matrix inverse actually means that the precoder treats interference as if it was noise.

To compute the value of the scalar $\frac{\lambda}{|\alpha|^2}$ we make the following definition:

$$\mathbf{F} = \mathbf{H}^H\mathbf{H}+\frac{\lambda}{|\alpha|^2}\mathbf{I} \tag{7}$$

Then $\mathbf{W_{tx}}$ can be rewritten as:

$$\mathbf{W_{tx}} = \frac{\alpha^*}{|\alpha|^2}\mathbf{F}^{-1}\mathbf{H_c}^H = \frac{\alpha^*}{|\alpha|^2}\widetilde{\mathbf{W}}_{\mathbf{tx}} \tag{8}$$

Now, we will differentiate with respect α^*:

$$\begin{aligned}\frac{\partial\mathcal{L}(\mathbf{W_{tx}},\alpha,\lambda)}{\partial\alpha^*} &= \alpha\,\mathrm{Tr}\left(\left(\mathbf{HW_{tx}}\right)\mathbf{R_u}\left(\mathbf{HW_{tx}}\right)^H+\mathbf{R_n}\right)-\\ &-\mathrm{Tr}\left(\mathbf{R_u}\left(\mathbf{H_cW_{tx}}\right)^H\right)\end{aligned} \tag{9}$$

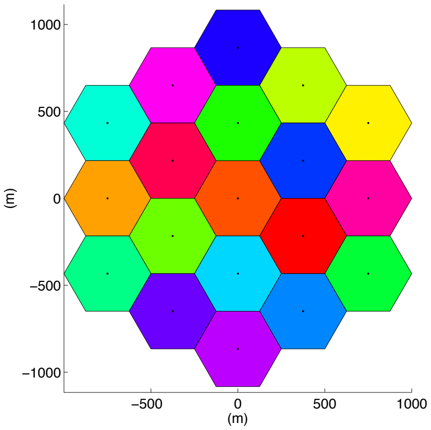

Fig. 2. Cell deployment for the simulation scenario.

and the value of α for which the Lagrangian has a singular point is:

$$\alpha = \frac{\mathrm{Tr}\left(\mathbf{R_u}\left(\mathbf{H_cW_{tx}}\right)^H\right)}{\mathrm{Tr}\left(\left(\mathbf{HW_{tx}}\right)\mathbf{R_u}\left(\mathbf{HW_{tx}}\right)^H+\mathbf{R_n}\right)} \tag{10}$$

Applying the power constraint we have:

$$\begin{aligned}P_{\mathrm{tx}} &= \mathrm{Tr}\left(\mathbf{W_{tx}R_uW_{tx}^H}\right) = \frac{1}{|\alpha|^2}\mathrm{Tr}\left(\widetilde{\mathbf{W}}_{\mathbf{tx}}\mathbf{R_u}\widetilde{\mathbf{W}}_{\mathbf{tx}}^H\right)\\ &= \frac{1}{|\alpha|^2}\mathrm{Tr}\left(\mathbf{F}^{-1}\mathbf{H_c}^H\mathbf{R_u}\mathbf{H_c}\mathbf{F}^{-1}\right)\\ &= \frac{1}{|\alpha|^2}\mathrm{Tr}\left(\mathbf{F}^{-2}\mathbf{H_c}^H\mathbf{R_u}\mathbf{H_c}\right)\end{aligned} \tag{11}$$

And from (11) and (10) it is easily shown:

$$\frac{\lambda}{|\alpha|^2} = \frac{\mathrm{Tr}\left(\mathbf{R_n}\right)}{P_{\mathrm{tx}}} \tag{12}$$

Enforcing the power constraint with equality, that is, $P_{\mathrm{tx}} = P_{\max}$ we get:

$$\mathbf{W_{tx}} = \frac{\alpha^*}{|\alpha|^2}\left(\mathbf{H}^H\mathbf{H}+\frac{\mathrm{Tr}\left(\mathbf{R_n}\right)}{P_{\max}}\mathbf{I}\right)^{-1}\mathbf{H_c}^H \tag{13}$$

with

$$|\alpha|^2 = \frac{P_{\max}}{\mathrm{Tr}\left(\left(\mathbf{H}^H\mathbf{H}+\frac{\mathrm{Tr}(\mathbf{R_n})}{P_{\max}}\mathbf{I}\right)^{-2}\mathbf{H_c}^H\mathbf{R_u}\mathbf{H_c}\right)} \tag{14}$$

an if we simply take α as a real number, then:

$$\alpha = \sqrt{\frac{P_{\max}}{\mathrm{Tr}\left(\left(\mathbf{H}^H\mathbf{H}+\frac{\mathrm{Tr}(\mathbf{R_n})}{P_{\max}}\mathbf{I}\right)^{-2}\mathbf{H_c}^H\mathbf{R_u}\mathbf{H_c}\right)}} \tag{15}$$

IV. PERFORMANCE STUDY

Our simulation scenario contains a set 19 base-stations as shown in Fig. 2. It consists of two tiers of base-stations arranged around a central BS. All the results are refered to such central base-station in order to avoid border effects. One user is positioned in each cell by drawing a sample from a uniform distribution whose support equals the hexagonal area assigned to that cell.

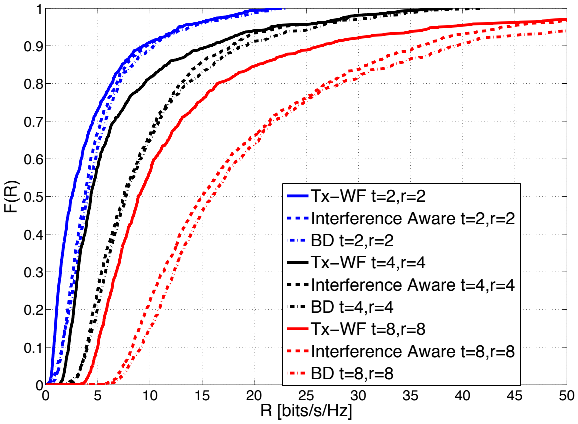

Fig. 3. Comparison of achievable rates for different antenna configuration and $\rho = 10$dB.

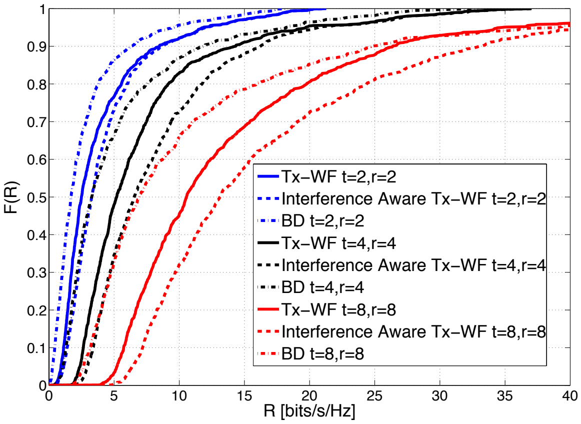

Fig. 4. Comparison of achievable rates for different antenna configuration and $\rho = 3$dB.

Assuming a standard LTE cell in a urban environment [10], the cell radius is assumed to be $R_{\text{cell}} = 250m$. The characteristics of the base-stations and the user equipments are also chosen according to typical LTE specifications. Base-stations are considered to transmit their signal using antennas with a gain of $G_{\text{tx}} = 14\,\text{dBi}$ and a maximum available power of $P_{\max} = 46$ dBm. On the other hand, user antennas are assumed to have neither gain nor losses, that is, they have a gain of $G_{\text{rx}} = 0\,\text{dBi}$. Signal propagation is also simulated according to the 3GPP models for LTE [10].

Distance dependent path loss is obtained as $\text{PL}(d) = 98.1 + 37.6\log_{10}(d)$ dB with d being the distance in meters. Besides, we include the Rayleigh fading between the k-th receive antenna of the i-th user placed at $\mathbf{y}_i$ and the l-th transmit antenna of the j-th base-station placed at $\mathbf{x}_j$ by drawing a coefficient r_{ij}^{kl} from a circularly symmetric complex Gaussian distribution with unit power. Each element of the channel matrix $\mathbf{H}$ is then evaluated as $(\mathbf{H})_{ir+k,jt+l} = \sqrt{\text{PL}\left(\|\mathbf{y}_i - \mathbf{x}_j\|\right)}r_{ij}^{kl}$.

The noise vector $\mathbf{n}$ at the input of the user antennas is assumed to be white and drawn from a complex Gaussian radially symmetric distribution. Its autocorrelation matrix is then of the form $\mathbf{R_n} = \sigma_n^2\mathbf{I}$ where σ_n^2 is obtained depending on the SNR at the cell border, $\rho = \frac{P_{\max}G_{\text{tx}}G_{\text{rx}}\text{PL}(R_{\text{cell}})}{\sigma_n^2}$.

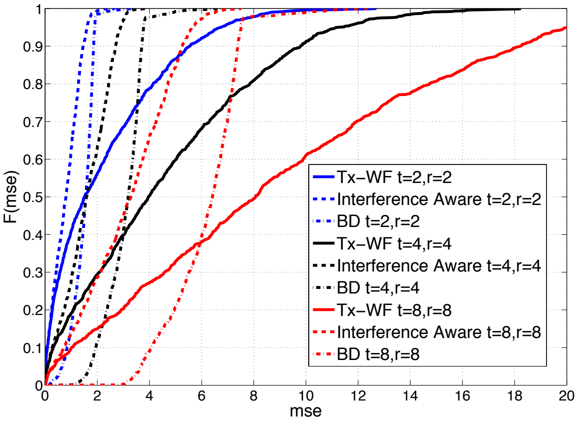

Fig. 5. MSE for different antenna configuration and $\rho = 10$dB.

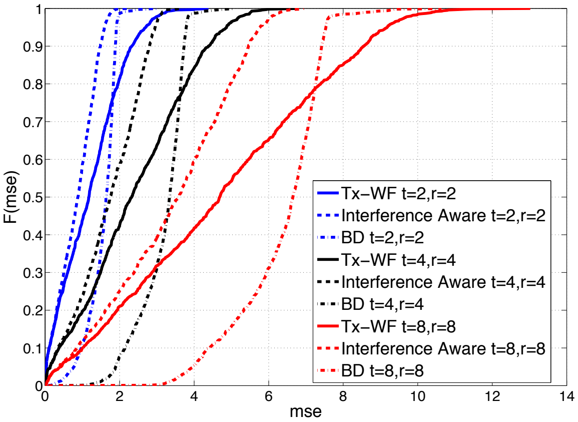

Fig. 6. MSE for different antenna configuration and $\rho = 3$dB.

In this scenario, we will simulate $N_{\text{rep}} = 1000$ different user deployments within the 19-cell network, and get the corresponding channel matrix. The proposed interference-aware precoder is compared to other designs in the literature. The first comparison is with a simple precoder design that does not take into account the interference from other cells. This design is one of the proposed precoders given in [4] and named Tx-WF. It should be noted that compared to our design in (13) the differences in the Tx-WF precoder formulation would be that the channel matrix inside the inverse would be $\mathbf{H_c}$ while in (13) we use $\mathbf{H}$ and $\mathbf{R_n^c}$ should be used instead of $\mathbf{R_n}$. The interference-aware filter is also compared with a fully coordinated scheme in which all BS know the channel and the user data of all communication links. The design is a full precoder matrix that allows a joint transmission from all BS to the users. This scheme is described in [3] and allows a block diagonalization of the full channel matrix. The power allocation scheme for the BD strategy is uniform.

The proposed precoder is compared with Tx-WF and BD performance by means of the cumulative density functions of the user achievable rate R and MSE. Different antenna configuration are used for this purpose: $t = 2, r = 2$, $t = 4, r = 4$, and $t = 8, r = 8$.

The first conclusion we can infer from Figs. 3-6 is that our interference aware filter outperforms the precoder in [4] in all scenarios. This should not be surprising since we have formulated our precoder as an improved version of the original Tx-WF to deal with other-cell interference. When comparing the performance of our design with BD, we have to take first into account that our design requires a much lesser amount of coordination between BS given that only channel knowledge is needed in the BS and there is no need for other cell user data knowledge. This translates into a lower amount of feedback needed for our solution. Therefore, one may expect that BD surpasses our simple interference aware MMSE-ZF design. However, as we can see from Figs. 4 and 6, at low SNR our design actually outperforms BD by a big margin. The fact that BD employs many more degrees of freedom does not compensate that its formulation completely disregards noise, which is relevant at low SNR. For high values of the SNR, we are clearly shifting towards scenarios where interference dominate over noise, and ZF based schemes usually achieve an excellent performance. However, according to Figs. 3 and 4, even in those scenarios our interference-aware design performs really close. In fact, it still outperforms BD in terms of MSE and gets rates only slightly below those achieves by BD.

A summary of the results shown in Figs. 3-6 is given in table I in terms of the mean and median rates in bits/s/Hz ($\overline{R}$ and $\widetilde{R}$ respectively) and mean and median MSE ($\overline{\mathsf{MSE}}$ and $\widetilde{\mathsf{MSE}}$ respectively) of each of the users in the system.

Configuration		Tx-WF	Int.-Aware	BD
$t = 2, r = 2, \rho = 3\text{dB}$	$\overline{R}$	3.9	4.4	2.7
	$\widetilde{R}$	2.5	3.3	1.7
	$\overline{\mathsf{MSE}}$	1.2	0.8	1.5
	$\widetilde{\mathsf{MSE}}$	1.2	0.9	1.6
$t = 2, r = 2, \rho = 10\text{dB}$	$\overline{R}$	4.0	4.9	5.2
	$\widetilde{R}$	2.5	3.8	3.9
	$\overline{\mathsf{MSE}}$	2.3	0.8	1.4
	$\widetilde{\mathsf{MSE}}$	1.5	0.8	1.6
$t = 4, r = 4, \rho = 3\text{dB}$	$\overline{R}$	7.1	8.5	5.3
	$\widetilde{R}$	5.2	6.5	3.3
	$\overline{\mathsf{MSE}}$	2.4	1.7	3.5
	$\widetilde{\mathsf{MSE}}$	2.3	1.7	3.3
$t = 4, r = 4, \rho = 10\text{dB}$	$\overline{R}$	6.9	9.5	10.0
	$\widetilde{R}$	4.3	7.5	7.7
	$\overline{\mathsf{MSE}}$	4.6	1.6	3.1
	$\widetilde{\mathsf{MSE}}$	4.0	1.6	3.2
$t = 8, r = 8, \rho = 3\text{dB}$	$\overline{R}$	14.2	17.1	11.2
	$\widetilde{R}$	10.5	13.2	7.0
	$\overline{\mathsf{MSE}}$	4.7	3.4	6.3
	$\widetilde{\mathsf{MSE}}$	4.7	3.6	6.6
$t = 8, r = 8, \rho = 10\text{dB}$	$\overline{R}$	13.1	19.1	20.8
	$\widetilde{R}$	8.9	15.1	16.0
	$\overline{\mathsf{MSE}}$	8.9	3.1	6.1
	$\widetilde{\mathsf{MSE}}$	8.1	3.3	6.4

TABLE I. COMPARISON OF AVERAGE AND MEDIAN VALUES OF THE USER RATE R AND PER-USER MSE ATTAINED BY TX-WF, INTERFERENCE-AWARE FILTER AND BD.

V. CONCLUSIONS

In this paper we have introduced a novel joint MMSE-ZF MIMO precoder design aimed at multi-cell environments which allows achieving trade-off between minimization of the intra-cell MSE and ICI cancellation. Such design provides a reduced complexity with respect to state-of-the-art MIMO linear precoding scheme being used in multi-cell scenarios such as BD by eliminating the need to equip users with full receive filters and avoiding the need of having each BS know the data to be sent to all users in the whole system. Besides, we have provided a closed-form solution so that the computational cost for obtaining such precoder is very reduced. Even though it is not a fully MMSE-based precoder, our simulation results show that the behaviour that its performance exhibits with changes in the SNR is much closer to that of a MMSE precoder than BD. Indeed, at low-SNR scenarios, our MMSE-ZF precoder outperforms BD significantly. At high-SNR scenarios, the throughput which BD achieves is only slightly higher even though its implementation is much more costly. Therefore, our proposal is a good step towards filling the lack of MMSE based precoders applicable multi-cell wireless systems.

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