Analysis of Orthogonal Transmit Beamforming Using Statistical Channel Information

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Abstract— **The multiple-access interference (MAI) is one of the major factors threatening the performance of multiuser systems. Transmit beamforming is a powerful strategy to increase the system capacity and mitigate interference. Traditional zero-forcing transmit beamforming (ZFBF) is an effective means to remarkably suppress MAI if the downlink channel is precisely known. However, it is very difficult to get exact information on the actual channel in realistic scenarios. In this paper, we present an approach to achieve orthogonal transmit beamforming (OTBF), only in virtue of statistical information of the downlink channel by using semidefinite programming tools. Different criteria are considered to solve the same problem by satisfying specific constraints between the total transmission power and the quality of service (QoS) requirements of individual users. Furthermore, robust designs for the presented approaches are also analyzed. Simulation results show the effectiveness and the robustness of these strategies.**

I. Introduction

The mutual interference among co-channel users limits the capacity of multiuser systems. Although the problem of interference-rejection has been traditionally addressed at the receiver end, more practical approaches should rather optimize the transmitter operation by efficiently suppressing the multiple-access interference (MAI) and increasing system capacity without needing to modify the receiver.

Transmit beamforming is an example of an effective approach to achieve the above-mentioned objectives. A considerable number of schemes for multiuser downlink beamforming have been proposed in the last years [1][2][3].

Traditional zero-forcing transmit beamforming (ZFBF) can suppress MAI by forcing all inter-user interference to zero. Consequently, the complexity of the data detection mechanism is considerably reduced since no interference suppression is, in principle, necessary at the mobile terminals. ZFBF is widely exploited in different contexts, such as in the downlink beamforming strategies associated to the scheduling in cross-layer designs [4]. Nevertheless, for conventional ZFBF, the transmitter must know the exact channel state information (CSI) in order to precisely cancel the interference. Otherwise, the performance of the system may degrade dramatically.

In practical systems, however, explicit CSI is rather difficult to be acquired. In this paper, the problem of orthogonal transmit beamforming (OTBF) is addressed by considering the ZFBF approach and by only using second-order statistical information of the channel, namely the channel correlation matrices. Three major design criteria are adopted: the minimization of the transmission power subject to a certain signal-to-interference-plus-noise-ratio (SINR) constraint for the intended users, and the maximization of both the minimum SINR and the minimum common information rate, respectively, subject to the total transmission power constraint. In order to obtain the optimum solutions efficiently, semidefinite optimization is applied according to the formulation of the previous criteria. Finally, practical errors in real systems are considered and robust schemes are also analyzed.

The rest of this paper is organized as follows. Section II describes the system model for multiuser system with multiple antennas at the transmitter. The proposed schemes are analyzed based on different criteria by using formulation adopted from semidefinite optimization in Section III. Section IV considers a robust solution in terms of a certain error situation. Finally, simulation results are presented in Section V and conclusions are drawn in Section VI.

II. System Model

Consider a multiple-input single-output (MISO) communication system with a single base station and K user terminals. The base station is equipped with N transmit antennas and each user has a single receive antenna. Let $\mathbf{w}_j$ be the N-dimensional transmit beamforming weight vector defined for the jth user. The signal transmitted from the antenna array is given by

$$\mathbf{x} = \sum_{j=1}^{K} s_j \mathbf{w}_j^H \tag{1}$$

where s_j is the data sequence intended for the user j. The signal received by the kth user can be expressed as

$$r_k = \sum_{j=1}^{K} s_j \mathbf{w}_j^H \mathbf{h}_k + n_k \quad 1 \leq k \leq K \tag{2}$$

where $\mathbf{h}_k$ denotes the N dimensional spatial channel response vector between the base station and the kth user. Throughout this paper, transmitted signals from antenna array are assumed to experiment a frequency-flat fading impulse response. Finally, n_k models the background additive white Gaussian noise with mean zero and variance σ_k^2 .

The received SINR for user k can be formulated as follows

$$SINR_k = \frac{\left|\mathbf{w}_k^H \mathbf{h}_k\right|^2}{\sum_{j=1,j\neq k}^{K} \left|\mathbf{w}_j^H \mathbf{h}_k\right|^2 + \sigma_k^2} \quad (3)$$

The traditional ZFBF criterion tries to force all co-channel interference to zero relying on a perfect channel knowledge for every user, i.e. $\mathbf{w}_k^H \mathbf{h}_k = 1$, $\mathbf{w}_k^H \mathbf{h}_j = 0$, $k \neq j$, $1 \leq k \leq K$. However, from a system implementation point of view, perfect CSI is difficult to obtain in real systems.

III. Orthogonal Transmit Beamforming Strategies

The general criterion to design a transmit beamforming scheme for multiuser systems is to consider balancing the specific constraints between transmission power at the base station and quality of service (QoS), i.e. the SINR requirement for individual users [5] and their ultimate data rate achieved. Here we base on three different concepts to design the OTBF scheme: the first seeks to minimize the total transmission power while fulfilling the received SINR requirement for each intended user; the other two criteria attempt to maximize either the minimum received SINR or the minimum common rate over all desired users under the constraint of the total transmission power.

It has been proved that the ZFBF strategy can achieve the same asymptotic sum-rate capacity as that of the optimal dirty paper coding (DPC) when the number of users is large enough [6]. Hence, a good system performance can be achieved by a relatively simple zero-forcing scheme.

Based on the idea of ZFBF, the OTBF problem is formulated by exploiting these different criteria, and semidefinite optimization techniques are employed to solve the problems only exploiting the (second-order) statistical channel information instead of an ideal channel knowledge.

To avoid using the exact channel gains to design the OTBF, statistical channel knowledge in the forward link can be recovered by exploiting the downlink-uplink reciprocity principle for time division duplex (TDD) systems and the feedback for frequency division duplex (FDD) systems. We can then obtain the second-order statistical information in the form of the correlation matrix $\mathbf{R}_k = \mathbb{E}\left[\mathbf{h}_k \mathbf{h}_k^H\right]$, $1 \leq k \leq K$, for each user in the system.

A. Formulation of minimum power strategy

The goal of this strategy is to minimize the total transmission power while guaranteeing a pre-defined received SINR for each individual user. The power transmitted for the kth user is proportional to the Euclidean norm of the corresponding weight vector, i.e. $p_k = \|\mathbf{w}_k\|_2^2 = \mathbf{w}_k^H \mathbf{w}_k$. Then this problem can be stated as follows

$$\begin{aligned} &\min \textstyle\sum_{k=1}^{K} p_k \\ &s.t. \quad SINR_k \geq \gamma_k \quad k = 1, 2, ..., K \end{aligned} \quad (4)$$

where γ_k is a certain threshold for the received SINR for user k. This formulation is equivalent to

$$\begin{aligned} &\min \textstyle\sum_{k=1}^{K} \mathbf{w}_k^H \mathbf{w}_k \\ &s.t. \frac{\mathbf{w}_k^H \mathbf{R}_k \mathbf{w}_k}{\sum_{j=1,j\neq k}^{K} \mathbf{w}_j^H \mathbf{R}_k \mathbf{w}_j + \sigma_k^2} \geq \gamma_k \quad k = 1, 2, ..., K \end{aligned} \quad (5)$$

where the left-hand term in the constraint represents the $SINR_k$ depending on the correlation matrices of the respective users. Note that since all beamforming vectors are involved in the constraint, a global solution must be found for the whole system. Note further that γ_k could be different for each user as different users may have associated different QoS requirements depending on the scenarios.

The original constraint set involves quadratic non-convex functions of the optimization variables. However, the structure of the problem allows us to recast it into the standard formulation used by SDP solvers, such as SeDuMi [7], which is a Matlab implementation of modern interior point methods [8] that can efficiently solve SDP programs. To that effect, we need to convert the vector variable $\mathbf{w}_k$ into the matrix variable $\mathbf{F}_k$ by defining $\mathbf{F}_k = \mathbf{w}_k \mathbf{w}_k^H$ and using the condition $\mathbf{w}_k^H \mathbf{w}_k = \mathrm{Tr}\left[\mathbf{w}_k \mathbf{w}_k^H\right]$ as well as the rotation property of the trace operator $\mathbf{w}_k^H \mathbf{R}_k \mathbf{w}_k = \mathrm{Tr}\left[\mathbf{R}_k \mathbf{w}_k \mathbf{w}_k^H\right] = \mathrm{Tr}\left[\mathbf{R}_k \mathbf{F}_k\right]$.

Thus, the previous formulation (5) can be rewritten as

$$\begin{aligned} &\min \textstyle\sum_{k=1}^{K} \mathrm{Tr}\left[\mathbf{F}_k\right] \\ &s.t. \ \mathrm{Tr}\left[\mathbf{R}_k \mathbf{F}_k\right] - \gamma_k \textstyle\sum_{j\neq k} \mathrm{Tr}\left[\mathbf{R}_k \mathbf{F}_j\right] \geq \gamma_k \sigma_k^2 \\ &\quad \mathbf{F}_k = \mathbf{F}_k^H \succeq 0 \qquad k = 1, 2, ..., K \end{aligned} \quad (6)$$

where the last constraint guarantees a Hermitian positive semidefinite $\mathbf{F}_k$. Note that there should be a rank 1 constraint for the matrix $\mathbf{F}_k$ in the above formulation, which would makes this problem non-convex, so we still have to rely on the rank relaxation of the matrix $\mathbf{F}_k$ to finally get to a standard SDP formulation. However, by using so-called Lagrangian relaxation techniques, it is shown in [9] that the optimal solution for the matrix $\mathbf{F}_k$ has indeed rank 1.

According to the OTBF approach, the signals transmitted to the desired user need to be orthogonal to the signals from the rest of the users in the system. Only this way will enable the interference from all other users in the system be directly (without further processing) removed from the signal received by the desired user. This can be introduced in our formulation as a constraint that can be expressed in an SDP standard form as $\mathrm{Tr}\left[\mathbf{R}_k \mathbf{F}_j\right] = 0, k \neq j$. Thus, the new formulation takes the following form

$$\begin{aligned} &\min \textstyle\sum_{k=1}^{K} \mathrm{Tr}\left[\mathbf{F}_k\right] \\ &s.t. \ \mathrm{Tr}\left[\mathbf{R}_k \mathbf{F}_k\right] \geq \gamma_k \sigma_k^2 \\ &\quad \mathrm{Tr}\left[\mathbf{R}_k \mathbf{F}_j\right] = 0 \qquad j \neq k \\ &\quad \mathbf{F}_k = \mathbf{F}_k^H \succeq 0 \qquad k = 1, 2, ..., K \end{aligned} \quad (7)$$

We can now define a new term with the interference from a certain user k to the rest of the users in the system as follows

$$Inf_{Tk} = \mathbf{w}_k^H \mathbf{Q}_k \mathbf{w}_k = \mathbf{w}_k^H \left(\textstyle\sum_{j\neq k} \mathbf{R}_j\right) \mathbf{w}_k \quad (8)$$

By forcing the interference term $Inf_{Tk}, \forall k$ to zero, the above problem can be rewritten as

$$\begin{aligned} &\min \textstyle\sum_{k=1}^{K} \mathrm{Tr}\left[\mathbf{F}_k\right] \\ &s.t. \;\; \mathrm{Tr}\left[\mathbf{R}_k \mathbf{F}_k\right] \geq \gamma_k \sigma_k^2 \\ &\qquad \mathrm{Tr}\left[\mathbf{Q}_k \mathbf{F}_k\right] = 0 \qquad j \neq k \\ &\qquad \mathbf{F}_k = \mathbf{F}_k^H \succeq 0 \qquad k = 1,2,...,K \end{aligned} \tag{9}$$

Again, modern interior-point optimization methods can be here employed to obtain a global optimum solution set $\{\mathbf{F}_k\}, k = 1, 2, \cdots K$.

B. Formulation of maximin SINR strategy

A related problem to the above one is the maximin problem, which maximizes the minimum received SINR over all users subject to a constraint on the total transmission power. Assuming the total available power at the base station is P, this problem can be stated as

$$\begin{aligned} &\max \min SINR_k \\ &s.t. \textstyle\sum_{k=1}^{K} p_k \leq P \qquad k = 1,2,...,K \end{aligned} \tag{10}$$

or equivalently

$$\begin{aligned} &\max_{\{\mathbf{w}_k\}} \min_{1<k<K} \frac{\mathbf{w}_k^H \mathbf{R}_k \mathbf{w}_k}{\sum_{j=1, j\neq k}^{K} \mathbf{w}_j^H \mathbf{R}_k \mathbf{w}_j + \sigma_k^2} \\ &s.t. \textstyle\sum_{k=1}^{K} \mathbf{w}_k^H \mathbf{w}_k \leq P \qquad k = 1,2,...,K \end{aligned} \tag{11}$$

As for the previously introduced method, the above optimization problem can be recast into a standard SDP program that can be efficiently solved using existing SDP method. Introducing an intermediate variable t, which can be regarded as the minimum SINR, the problem can be formulated as

$$\begin{aligned} &\max \quad t \\ &s.t. \;\; \mathrm{Tr}\left[\mathbf{R}_k \mathbf{F}_k\right] \geq t\sigma_k^2 \\ &\qquad \mathrm{Tr}\left[\mathbf{R}_k \mathbf{F}_j\right] = 0 \qquad j \neq k \\ &\qquad \textstyle\sum_{k=1}^{K} \mathrm{Tr}\left[\mathbf{F}_k\right] \leq P \\ &\qquad \mathbf{F}_k = \mathbf{F}_k^H \succeq 0 \qquad k = 1,2,...,K \end{aligned} \tag{12}$$

C. Formulation of maximin common information rate strategy

In some cases, the design objective of the multiuser system is to optimize the sum-rate of the system. For a multiuser transmit beamforming scheme the sum-rate can be expressed as [10]

$$\begin{aligned} &R_{BF} = \max \sum_{k=1}^{K} \log\left(\frac{1 + \sum_{j=1}^{K} \left|\mathbf{w}_j^H \tilde{\mathbf{h}}_k\right|^2}{1 + \sum_{j=1, j\neq k}^{K} \left|\mathbf{w}_j^H \tilde{\mathbf{h}}_k\right|^2} \right) \\ &s.t. \textstyle\sum_{k=1}^{K} \mathbf{w}_k^H \mathbf{w}_k \leq P \qquad k = 1,2,...,K \end{aligned}$$

where $\tilde{\mathbf{h}}_k$ is the normalized channel vector. If our OTBF concept is considered, the received signal at the kth-user's terminal consists only of the desired data and the background noise, but contains no interference from any other users. Then, single-user detection without further processing can be effectively employed at the receiver. Hence, it follows that the maximum achievable data rate for the kth user is attained, and thus the sum-rate can be changed into

$$\begin{aligned} &R_{OTBF} = \max \sum_{k=1}^{K} \log\left(1 + \left|\mathbf{w}_k^H \tilde{\mathbf{h}}_k\right|^2\right) \\ &s.t. \textstyle\sum_{k=1}^{K} \mathbf{w}_k^H \mathbf{w}_k \leq P \qquad k = 1,2,...,K \end{aligned} \tag{13}$$

Here we consider maximizing the common information rate instead of trying to obtain the optimal sum-rate in order to achieve fairness among different users, so that it can also be formulated in the maximin form (including now the noise variance term) as

$$\begin{aligned} &\max_{\{\mathbf{w}_k\}} \min_{1<k<K} \log\left(1 + \frac{\left|\mathbf{w}_k^H \mathbf{h}_k\right|^2}{\sigma_k^2}\right) \\ &s.t. \;\; \textstyle\sum_{k=1}^{K} \mathbf{w}_k^H \mathbf{w}_k \leq P \qquad k = 1,2,...,K \end{aligned} \tag{14}$$

It is clear that the deterministic channel vectors are used in the above expression. But when the channel is random, the mean data rate need to be taken into account, which is expressed as

$$\bar{r}_k = \mathbb{E}_{\mathbf{h}}\left[\log\left(1 + \frac{\mathbf{w}_k^H \mathbf{h}_k \mathbf{h}_k^H \mathbf{w}_k}{\sigma_k^2}\right)\right] \tag{15}$$

In order to study the influence of channel correlation matrix on data rate, we introduce a new relation as follows

$$\bar{r}_k \leq r_{k\_bound} = \log\left(1 + \mathbb{E}_{\mathbf{h}}\left[\frac{\mathbf{w}_k^H \mathbf{h}_k \mathbf{h}_k^H \mathbf{w}_k}{\sigma_k^2}\right]\right) \tag{16}$$

which holds due to Jensen's inequality and concavity of $\log(\cdot)$ function [11], and then it can be further reduced to

$$\bar{r}_k \leq r_{k\_bound} = \log\left(1 + \mathbf{w}_k^H \tilde{\mathbf{R}}_k \mathbf{w}_k\right) \tag{17}$$

where $\tilde{\mathbf{R}}_k = \mathbb{E}\left[\tilde{\mathbf{h}}_k \tilde{\mathbf{h}}_k^H\right]$ and $\tilde{\mathbf{h}}_k = \mathbf{h}_k / \sigma_k$. Therefore, this method would provide an upper bound on the mean data rate. For the sake of simplicity, we only consider the case when this bound is held in the following.

Thus, the optimization problem (14) can be recast into

$$\begin{aligned} &\max \quad t \\ &s.t. \;\; \log\left(1 + \mathrm{Tr}[\tilde{\mathbf{R}}_k \mathbf{F}_k]\right) \geq t \\ &\qquad \mathrm{Tr}[\tilde{\mathbf{R}}_k \mathbf{F}_j] = 0 \qquad j \neq k \\ &\qquad \textstyle\sum_{k=1}^{K} \mathrm{Tr}\left[\mathbf{F}_k\right] \leq P \\ &\qquad \mathbf{F}_k = \mathbf{F}_k^H \succeq 0 \qquad k = 1,2,...,K \end{aligned} \tag{18}$$

After removing the "*log*" function in virtue of its monotonicity, the above problem is seen to be equivalent to

$$\begin{aligned} &\max \quad \tilde{t} \\ &s.t. \;\; \mathrm{Tr}[\tilde{\mathbf{R}}_k \mathbf{F}_k] \geq \tilde{t} \\ &\qquad \mathrm{Tr}[\tilde{\mathbf{R}}_k \mathbf{F}_j] = 0 \qquad j \neq k \\ &\qquad \textstyle\sum_{k=1}^{K} \mathrm{Tr}\left[\mathbf{F}_k\right] \leq P \\ &\qquad \mathbf{F}_k = \mathbf{F}_k^H \succeq 0 \qquad k = 1,2,...,K \end{aligned} \tag{19}$$

which is identical to the aforementioned maximin SINR strategy. According to this, we see that the maximin SINR strategy achieves also the upper bound of maximum common information rate.

IV. Robust Solutions

In practical systems, the available channel knowledge is generally an imperfect version of the actual channel. In this case, the uncertainty in the channel estimation should be taken into consideration and robust schemes should be accordingly designed. At the transmitter, the CSI can be obtained from the previous uplink measurement in TDD systems or through a feedback channel in FDD systems. Different sources of errors can be identified depending on the CSI acquisition method. In TDD systems, the main error sources can be considered to be the error accomplished by the channel estimator, which can be modeled for some methods as zero-mean Gaussian noise, and outdated estimates because of channel variations. On the other hand, in FDD systems the errors have mainly their origin in the estimate quantization process at the mobile terminals and in the feedback process.

In the above analysis it is assumed that no errors are involved. If we now take into account the error inherent to the channel estimation method, a robust scheme can be obtained. To that effect, we consider that the true channel impulse response $\mathbf{h}_k$ is estimated with a certain error Δ_{hk} with correlation matrix Θ_{hk} and assumed independent of the channel estimate $\hat{\mathbf{h}}_k$ i.e. $\mathbf{h}_k = \hat{\mathbf{h}}_k + \Delta_{hk}$. This error is further assumed to be of (known) bounded energy, i.e. $\mathbb{E}\left[\|\Delta_{hk}\|_2^2\right] = \mathrm{Tr}\left[\Theta_{hk}\right] \leq \varepsilon_{hk}$. Under these assumptions, the actual correlation matrix can be expressed as

$$\mathbf{R}_k = \mathbb{E}\left[(\hat{\mathbf{h}}_k + \Delta_{hk})(\hat{\mathbf{h}}_k + \Delta_{hk})^H\right] = \hat{\mathbf{R}}_k + \Theta_{hk} \quad (20)$$

where $\hat{\mathbf{R}}_k = \mathbb{E}\left[\hat{\mathbf{h}}_k \hat{\mathbf{h}}_k^H\right]$ and $\Theta_{hk} = \mathbb{E}\left[\Delta_{hk}\Delta_{hk}^H\right]$.

By doing so, we now have

$$\mathrm{Tr}\left[\mathbf{R}_k\mathbf{F}_k\right] = \mathrm{Tr}\left[(\hat{\mathbf{R}}_k + \Theta_{hk})\mathbf{F}_k\right] = \mathrm{Tr}\left[\hat{\mathbf{R}}_k\mathbf{F}_k\right] + \mathrm{Tr}\left[\Theta_{hk}\mathbf{F}_k)\right] \quad (21)$$

Applying the Cauchy-Schwarz inequality to the second summand in (21), we get

$$\begin{aligned} \mathrm{Tr}\left[\Theta_{hk}\mathbf{F}_k\right] &= \mathbb{E}\left[\mathrm{Tr}\left[\Delta_{hk}^H \mathbf{w}_k \mathbf{w}_k^H \Delta_{hk}\right]\ \right] \quad (22) \\ &= \mathbb{E}\left[\left|\Delta_{hk}^H \mathbf{w}_k\right|^2\right] \leq \mathbb{E}\left[\|\Delta_{hk}\|_2^2\right] \|\mathbf{w}_k\|_2^2 \\ &\leq \varepsilon_{hk}\,\mathrm{Tr}\left[\mathbf{F}_k\right] \end{aligned}$$

Hence, the optimal robust beamforming design, using the maximin SINR strategy as an example, can be formulated in a standard SDP form as

$$\begin{aligned} &\max \quad t \\ &s.t. \;\; \mathrm{Tr}[\hat{\mathbf{R}}_k\mathbf{F}_k] \geq t\sigma_k^2 + \varepsilon_{hk}\,\mathrm{Tr}\left[\mathbf{F}_k\right] \\ &\qquad \mathrm{Tr}[\hat{\mathbf{R}}_k\mathbf{F}_j] \leq \varepsilon_{hk}\,\mathrm{Tr}\left[\mathbf{F}_j\right] \quad (23) \\ &\qquad \textstyle\sum_{k=1}^K \mathrm{Tr}\left[\mathbf{F}_k\right] \leq P \\ &\qquad \mathbf{F}_k = \mathbf{F}_k^H \succeq 0 \qquad k = 1, 2, ..., K \end{aligned}$$

V. Simulation Results

In this section, we present the performance of the above transmit beamforming schemes for a system with one base station and K single-antenna users. The base station is equipped with a uniform linear array (ULA) with $N = 8$ elements (spaced half a wavelength apart). The angle spread for each user is assumed to be 2 degrees around its main angle of departure (AOD). The SDP solver SeDuMi [7] is used to obtain the optimum global solution for each strategy.

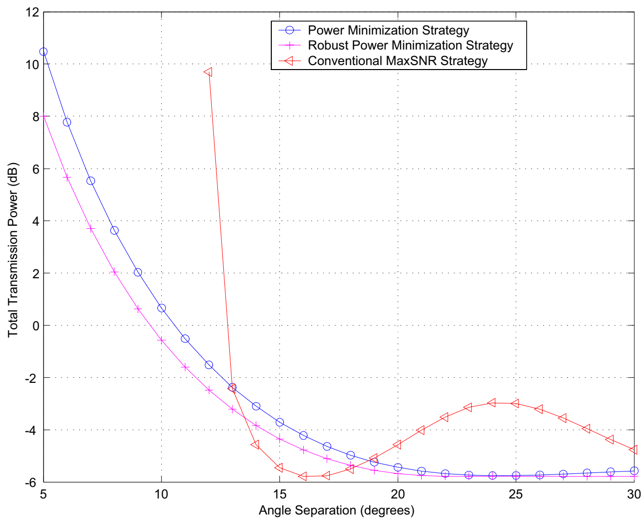

Fig. 1. Total transmission power versus angle separation

First, we consider a system with $K = 2$ users: one is located at 20 degrees and the other moves from 25 to 50 degrees. The SINR constraints γ_i are set to be 10dB for both users. Figure 1 shows the result of minimizing the transmission power and its associated robust strategy. Moreover, the conventional beamforming in which the beamforming vectors are chosen as the principle eigenvectors of respective $\mathbf{R}_k$ is used for comparison. It can be seen that the transmission power decreases as the angular separation between users increases since it is easier to separate different users when they are far from each other. On the other hand, the robust strategy ($\varepsilon_{hk} = 0.001$) dedicates relatively lower power to obtain the same SINR because it does not force all interference exactly to zero due to the estimation errors taken into account. However, the conventional beamforming can only satisfies the SINR constraint when angle separation is larger than 13 degrees, and for most cases it also requires more transmission power than the proposed schemes.

Note that if we let the maximin SINR strategy use the same power constraint as indicated in the curve of minimizing transmission power strategy, the same SINR is obtained for both users, being almost equal to 10dB. Moreover, because the maximin common information rate strategy has the same final formulation as the maximin SINR strategy, both approaches get the same result. Due to space limitations this result was not included here. Therefore, it is shown that the three OTBF strategies present very similar performance if the same SINR requirements are assumed for all users.

In Figures 2 and 3 we consider a situation with $K = 3$ users and the performance of the maximin SINR strategy is analyzed. The AOD of each user is assumed to be 20, 40

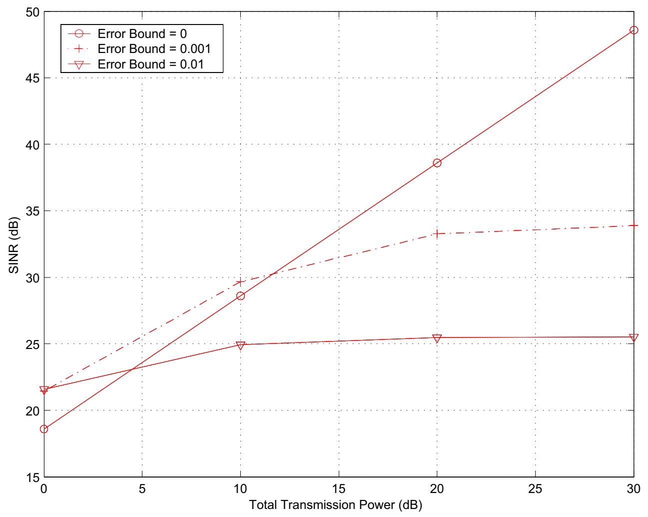

Fig. 2. Analysis of the maximin SINR strategy

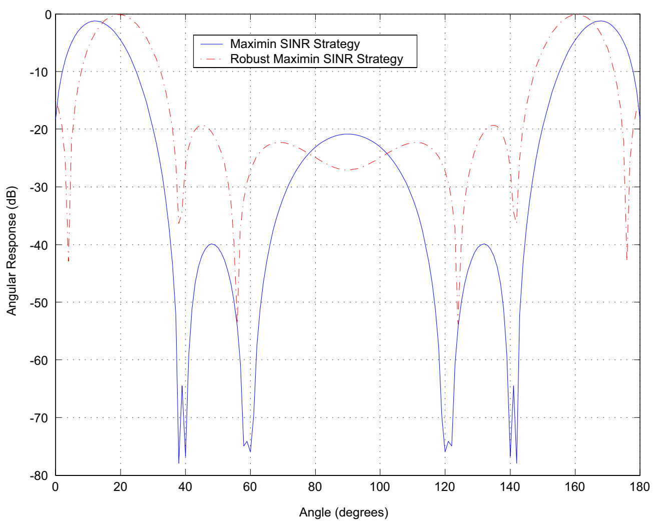

Fig. 3. Angular response of the maximin SINR strategy

and 60 degrees. Figure 2 shows the relationship between the transmission power and received SINR for the middle user. The line in the figure with the circle shows how the SINR increases linearly with an increasing transmission power as all the interferences are almost totally suppressed. However, the SINR gets worse as the error energy bound ε_{hk} increases due to a deficient cancellation of the interference for inexact channel knowledge, and when the transmission power is increased, the interference caused by other users is relatively increased. Figure 3 shows the beampattern obtained in the above case for the AOD of the first user which is 20 degrees. It shows how the maximin SINR strategy places the main lobe in the direction of the desired user and creates deep "zeros" for the interferences, whereas the robust one generates a relatively wide main lobe and shallow zeros in the directions of the interferences in order to be capable of improving the robustness against the channel information errors.

VI. Conclusions

OTBF schemes based on channel statistical information are studied in this paper. We considered three different design strategies: minimizing the transmission power under individual received SINR constraints for different users in the system and maximizing the minimum received SINR or the minimum common rate for each user under the constraint of the total transmission power. Although the original formulation of these strategies result in non-convex optimization problems, they can be reformulated into standard SDP programs that can be efficiently solved by existing software implementations of modern interior-point methods. Uncertainty on the channel impulse response is also considered and robust design is accordingly proposed. Simulation results show the ability of the proposed OTBF schemes to suppress co-channel interference, and they also show the performance of the robust schemes as well as the equivalence of different strategies for certain scenarios.

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References

[1] F. Rashid-Farrokhi, K. J. R. Liu, and L. Tassiulas, "Joint optimal power control and beamforming in wireless networks using antenna arrays," *IEEE Trans. on Commun.*, vol. 46, pp. 1313–1323, Oct. 1999.
[2] F. Rashid-Farrokhi, K. J. R. Liu, and L. Tassiulas, "Transmit beamforming and power control for cellular wireless systems," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1437–1450, Oct. 1998.
[3] A. Yener, R. D. Yates, and S. Ulukus, "Interference management for CDMA systems through power control, multiuser detection, and beamforming," *IEEE Trans. on Commun.*, vol. 49, pp. 1227–1239, July 2001.
[4] D. Bartolome and A. I. Perez-Neira, "Multiuser spatial scheduling in the downlink of wireless systems," in *IEEE SAM'04*, Sitges,Spain, July 2004.
[5] M. Schubert and H. Boche, "Solution of the multi-user downlink beamforming problem with individual sinr constraints," *IEEE Trans. on Vehicular Tech.*, vol. 53, no. 1, pp. 18–28, Jan. 2004.
[6] T. Yoo and A. J. Goldsmith, "Optimality of zero-forcing beamforming with multiuser diversity," in *IEEE ICC'05*, May 2005.
[7] J. F. Sturm, *Using SeDuMi 1.02, a MATLAB toolbox for optimization over symmetric cones*, Department of Quantitative Economics, Maastricht University, The Netherlands, http://fewcal.kub.nl/-sturm/software/sedumi.html, 1999.
[8] Y. E. Nesterov and A. S. Nemirovski, "Interior-point polynomial methods in convex programming," in *SIAM Studies in Applied Mathematics*, SIAM Publications, Philadelphia, 1994.
[9] M. Bengtsson and B. Ottersten, "Downlink beamformer design using semidefinite optimization," in *RadioVetenskap och Kommunikation(RVK)*, May 1999, pp. 289–293.
[10] H. Viswanathan, S. Venkatesan, and H. Huang, "Downlink capacity evaluation of cellular networks with known-interference cancellation," *IEEE J. Select. Areas Commun.*, vol. 21, no. 5, pp. 802–811, June 2003.
[11] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, Wiley, New York, 1991.