INTERFERENCE ROBUSTNESS FOR CELLULAR MIMO NETWORKS

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ABSTRACT

Uncertainty in the spatial signature of interfering signals is a major source of performance degradation in the downlink of a MIMO network. In general, the exact transmit covariance matrix of the other transmitters can not be predicted correctly in advance as the optimal strategies mutually depend on each other. In this work, we investigate two approaches for optimizing downlink transmission that are robust to interference, while operating in absence of cross channel information at the transmitter. Although they may seem unrelated, the two approaches share an interesting symmetry and are both derived from a more general minimax duality.

1. INTRODUCTION

The interdependence of user data rates in the downlink of a wireless cellular network, due to interference and shared resources, makes it difficult to optimize the physical layer parameters. This is especially challenging in MIMO networks as the availability of additional degrees of freedom is directly reflected in the spatial signature of the interference.

In theory, interference can be completely eliminated by joint encoding over multiple transmitters, which however requires a huge amount of additional complexity and signaling; it might be difficult to implement in practice. Therefore, it is worthwhile to consider interference coordination for single cell signal processing, also known as coordinated beamforming and scheduling, where the remaining inter-cell interference is treated as additional noise. The spatial degrees of freedom provided by the multiple transmit antennas can be used for advanced interference coordination, for example by optimization techniques [1], or by targeting the maximally available degrees of freedom [2]. Still, these approaches are demanding concerning the channel state information (CSI) available at the transmitters, usually the channels between the users and the interfering transmitters need to be known. And yet, it is not clear, if the gains achieved do compensate for the costs to acquire cross-channel CSI in state-of-the-art deployable networks. In this work, we limit our attention to interference management that does not depend on cross-channel CSI at the transmitter, thus avoiding additional feedback. An example is fractional reuse [3], where interference is managed by providing protected resources for cell-edge users and allowing shared resources for those users that can afford an increased noise level.

In general, the spatial structure of the interference plus noise matrix can not be predicted correctly in advance and this uncertainty is a major source of performance degradation. The degradation of the transmission rates due to unexpected changes of the inter-cell interference is sometimes called "flash-light" effect [4] and several ideas are suggested to handle the problem [5]. Additionally, the uncertainty in interference results in uncertainty in the presumed achievable data rates of the users, which in turn causes impairments at the higher layers, for example the scheduler or the mechanism to allocate protected and unprotected bands for fractional reuse.

To increase robustness for the remaining inter-cell interference we consider two possible techniques. The first one considers interference by a worst case approximation, as for example done for the point-to-point MIMO channel or sum-rate maximization in [6,7]. The second method uses a definite shaping constraint on the sum covariance of the transmit symbols, therefore allowing for a less pessimistic approximation of the interference. Constraints on the sum covariance have been addressed in literature, for example a per antenna power constraint [8] or multiple linear constraints [9].

For both techniques we present algorithms to optimize the downlink transmit covariances for a weighted sum of the user rates, assuming dirty paper coding. The optimization is performed in the dual uplink, for which we provide an uplink-downlink relationship derived from the general minimax duality under linear conic constraints introduced in [10].

1.1. System Model

Consider the downlink of a cellular network with set of users $\mathcal{K}, K = |\mathcal{K}|$ and set of transmitters $\mathcal{T}, T = |\mathcal{T}|$. For simplicity, but without loss of generality, we assume that every user has N_{rx} receive antennas and every transmitter has N_{tx} antennas. The channel between user k and its serving transmitter is $\boldsymbol{H}_k \in \mathbb{C}^{N_{\text{rx}} \times N_{\text{tx}}}$ and we denote the channel to an interfering transmitter t by $\boldsymbol{H}_{kt} \in \mathbb{C}^{N_{\text{rx}} \times N_{\text{tx}}}$. For a user k and set of interfering transmitters $\mathcal{I}_k \subseteq \mathcal{T}$, the noise plus inter-cell interference covariance matrix is given by

$$\boldsymbol{R}_k = \boldsymbol{R}_{\eta,k} + \sum_{t\in\mathcal{I}_k} \boldsymbol{H}_{kt}\boldsymbol{Q}_t\boldsymbol{H}_{kt}^{\mathrm{H}}, \tag{1}$$

where $\boldsymbol{R}_{\eta,k}$ is the receiver noise covariance at the k-th user and $\boldsymbol{Q}_t$ is the sum transmit covariance of transmitter t. The noise plus (inter-cell) interference covariances of the users are

$$\mathcal{R} = (\boldsymbol{R}_k : k \in \mathcal{K}),$$

and the transmit covariances are

$$\mathcal{Q} = (\boldsymbol{Q}_k : k \in \mathcal{K}).$$

The sum transmit covariance of transmitter t is $\boldsymbol{Q}_t = \sum_{k\in\mathcal{K}_t} \boldsymbol{Q}_k$, where $\mathcal{K}_t, K_t = |\mathcal{K}_t|$ is the set of users served by transmitter t. The users $\mathcal{K}_t$ are served with covariances $\mathcal{Q}_t = (\boldsymbol{Q}_k : k \in \mathcal{K}_t)$ and their noise plus interference covariances are $\mathcal{R}_t = (\boldsymbol{R}_k : k \in \mathcal{K}_t)$. The data rate of user k is $r_k(\mathcal{Q}_t, \boldsymbol{R}_k)$ and depends on (some of) the other transmit covariances (intra-cell interference) and the noise plus inter-cell interference covariance (1), that includes the dependence on the transmission strategies of the interfering cells. Assuming dirty paper coding and users sorted according to the encoding order, the data rate is

$$r_k(\mathcal{Q}_t, \boldsymbol{R}_k) = \log\left(\frac{\left|\boldsymbol{I} + \boldsymbol{R}_k^{-1}\boldsymbol{H}_k \sum_{i\in\mathcal{K}_t, i\geq k} \boldsymbol{Q}_i \boldsymbol{H}_k^{\mathrm{H}}\right|}{\left|\boldsymbol{I} + \boldsymbol{R}_k^{-1}\boldsymbol{H}_k \sum_{i\in\mathcal{K}_t, i> k} \boldsymbol{Q}_i \boldsymbol{H}_k^{\mathrm{H}}\right|}\right). \tag{2}$$

We target the optimization of a weighted sum of the data rates, $\sum_{k\in\mathcal{K}} w_k r_k(\mathcal{Q}, \boldsymbol{R}_k)$, where w_k is the weight of user k. In order to optimize the downlink transmission strategies, we consider a virtual uplink problem, with flipped channels and roles of receivers and transmitters inverted. For a single cell with transmitter t, the uplink noise covariance is $\boldsymbol{\Omega}_t$ and the transmit covariances are

$$\mathcal{S}_t = (\boldsymbol{\Sigma}_k : k \in \mathcal{K}_t).$$

The data rate of user k in the uplink is denoted as $r_k(\mathcal{S}_t, \boldsymbol{\Omega}_t)$.

1.2. Interference Prediction

We do not regard interference coordination in the spatial domain and therefore each transmitter chooses the best transmit strategy for its users egoistically. For networks where each transmitter is equipped with a single antenna it is clear that the strategy of each transmitter is to use all available power, which makes the interference caused to users in a neighboring cell very well predictable, for example by measurements. As in the single antenna case, for multiple transmit antennas each transmitter will use its full power budget, however the spatial signature of the interference is difficult to predict. In case the interference could be predicted correctly in advance $\boldsymbol{R}_k$ is known for every user and the capacity achieving transmit strategies can be computed by considering an effective channel $\bar{\boldsymbol{H}}_k = \boldsymbol{R}_k^{-1/2}\boldsymbol{H}_k$. However, it is clear that the optimal transmit strategies mutually depend on each other, meaning we do not know the inter-cell interference in advance and the unpredictability of the interference causes problems for link rate adaptation.

The state of the art approach is to use an prediction of the inter-cell interference based on either measured ICI in the past [5], or based on knowledge of the cross-channels. In case the users are able to gather correct channel state information on the channels to the interfering transmitters, a prediction used in [3] is to assume a white transmit covariance using the full power budget P. The predicted interference plus noise covariance is then given by

$$\tilde{\boldsymbol{R}}_k = \boldsymbol{R}_{\eta,k} + \frac{P}{N_{\text{tx}}} \sum_{t\in\mathcal{I}_k} \boldsymbol{H}_{kt}\boldsymbol{H}_{kt}^{\mathrm{H}}. \tag{3}$$

A frequently observed alternative is to use a white noise matrix for the prediction.

2. MINIMAX UPLINK–DOWNLINK DUALITY

Lagrangian duality for a minimax Gaussian mutual information expression was introduced by [11] to prove the sum-capacity of the multi-user downlink. In [10] a minimax uplink-downlink duality for multi-user systems is introduced. Instead of the usual power constraint, the optimization of the downlink transmit covariances

$$\max_{\substack{\mathcal{Q}_t, \boldsymbol{Z}\in\mathcal{Z} \\ \boldsymbol{Q}_t \preceq \boldsymbol{C}+\boldsymbol{Z}}} \sum_{k\in\mathcal{K}_t} w_k r_k(\mathcal{Q}_t, \boldsymbol{R}_k),$$

includes a linear conic constraint on the sum covariance of a transmitter, such that

$$\boldsymbol{Q}_t \preceq \boldsymbol{C} + \boldsymbol{Z}, \boldsymbol{Z} \in \mathcal{Z}, \tag{4}$$

where $\mathcal{Z}$ is a linear subspaces of $N_{\text{tx}} \times N_{\text{tx}}$ Hermitian matrices and $\boldsymbol{C}$ is fixed. The downlink strategies are optimized under a worst case noise assumption. The noise covariances are constraint by

$$(\boldsymbol{R}_k : k \in \mathcal{K}_t) \in \mathcal{Y}^{\perp},$$

where $\mathcal{Y}^{\perp}$ is a linear subspace of K_t-tuple of appropriately sized Hermitian matrices, and

$$\sum_{k\in\mathcal{K}_t} \operatorname{tr}(\boldsymbol{B}_k\boldsymbol{R}_k) = \sigma^2,$$

with fixed $(\boldsymbol{B}_k : k \in \mathcal{K}_t)$ and σ^2.

The downlink minimax problem is

$$\min_{\substack{(\boldsymbol{R}_k : k\in\mathcal{K}_t)\in\mathcal{Y}^{\perp} \\ \sum_{k\in\mathcal{K}_t} \operatorname{tr}(\boldsymbol{B}_k\boldsymbol{R}_k)=\sigma^2}} \max_{\substack{\mathcal{Q}_t, \boldsymbol{Z}\in\mathcal{Z} \\ \boldsymbol{Q}_t \preceq \boldsymbol{C}+\boldsymbol{Z}}} \sum_{k\in\mathcal{K}_t} w_k r_k(\mathcal{Q}_t, \boldsymbol{R}_k). \tag{5}$$

Although the constraints are convex, the rate expression (2) in the utility renders the problem non-convex, which does not lead to an efficient method for finding a solution. However, there exists an equivalent uplink minimax problem

$$\min_{\substack{\boldsymbol{\Omega}_t \succ \mathbf{0}, \boldsymbol{\Omega}_t \in \mathcal{Z}^\perp \\ \operatorname{tr}(\boldsymbol{C}\boldsymbol{\Omega}_t)=\sigma^2}} \max_{\substack{\mathcal{S}_t, (\boldsymbol{Y}_k : k \in \mathcal{K}_t) \in \mathcal{Y} \\ \boldsymbol{\Sigma}_k \preceq \boldsymbol{B}_k + \boldsymbol{Y}_k \forall k \in \mathcal{K}_t}} \sum_{k \in \mathcal{K}_t} w_k r_k(\mathcal{S}_t, \boldsymbol{\Omega}_t), \quad (6)$$

where $\mathcal{Y}$ and $\mathcal{Z}^\perp$ are the orthogonal subspaces of $\mathcal{Y}^\perp$ and $\mathcal{Z}$, respectively. The uplink minimax problem is concave in the transmit covariances and convex in the noise covariance and therefore efficient methods to compute a solution are available. In the next section, we show how the minimax duality can be used to compute robust downlink strategies.

3. ROBUST DOWNLINK STRATEGIES

As inter-cell interference is considered by the prediction, the downlink problem decouples into individual problems per transmitter. In the following, we introduce two methods that allow to optimize the downlink transmit strategies such that they are robust to interference. For both methods, we first motivate and state the corresponding downlink optimization problem. We then identify the parameters to reformulate the problem as in (5), which directly gives us the corresponding uplink problem structure (6). The downlink transmit covariances are computed by the conventional uplink-downlink conversion, which is formulated explicitly in [12].

3.1. Worst Case Noise

As done for the point-to-point MIMO channel in [6, 7], we use a worst case approximation of the interference plus noise, which is obtained by assuming an arbitrary structure under a power constraint, i. e., $\operatorname{tr}(\boldsymbol{R}_k) = \sigma_k^2$. By using an effective channel $\bar{\boldsymbol{H}}_k = \frac{1}{\sigma_k}\boldsymbol{H}_k$, we can model the the worst case approximation by $\operatorname{tr}(\boldsymbol{R}_k) = 1$. The constant σ_k^2 should be related to the thermal noise covariance and the interfering channels. In case the cross channels are known at the receiver, we can select an upper bound by

$$\sigma_k^2 = \operatorname{tr}(\boldsymbol{R}_{\eta,k}) + \max\left\{ \sum_{t \in \mathcal{I}_k} \operatorname{tr}\left(\boldsymbol{H}_{kt}\boldsymbol{Q}_t\boldsymbol{H}_{kt}^{\mathrm{H}}\right) : \operatorname{tr}(\boldsymbol{Q}_t) = P \; \forall t \right\}, \quad (7)$$

which requires to compute the maximal singular values of the cross-channels.

The downlink transmit covariances are optimized subject to a sum power constraint. For the worst case approximation we obtain the following minimax problem:

$$\min_{\mathcal{R}_t} \left\{ \max_{\mathcal{Q}_t, \operatorname{tr}(\boldsymbol{Q}_t)=P} \left\{ \sum_{k \in \mathcal{K}_t} w_k r_k(\mathcal{Q}_t, \boldsymbol{R}_k) \right\} : \operatorname{tr}(\boldsymbol{R}_k) = 1 \forall k \right\}.$$

According to [10], the sum-power constraint can be modeled as

$$\boldsymbol{C} = \frac{P}{N_{\text{tx}}}\boldsymbol{I} \text{ and } \mathcal{Z} = \{\boldsymbol{Z} : \operatorname{tr}\{\boldsymbol{Z}\} = 0\}. \quad (8)$$

The one dimensional orthogonal subspace is

$$\mathcal{Z}^\perp = \{\boldsymbol{Z} : \boldsymbol{Z} = \lambda\boldsymbol{I}, \lambda \in \mathbb{R}\},$$

and $\operatorname{tr}(\boldsymbol{C}\boldsymbol{\Omega}_t) = 1$ yields $\boldsymbol{\Omega}_t = \frac{1}{P}\boldsymbol{I}$. Next, we find the model for the worst case noise approximation. First, we select $\mathcal{Y}^\perp$ as all Hermitian matrices $(\boldsymbol{R}_k : k \in \mathcal{K}_t)$ where

$$\operatorname{tr}(\boldsymbol{R}_j) = \operatorname{tr}(\boldsymbol{R}_k) \forall j, k \in \mathcal{K}_t.$$

Second, if we set $\boldsymbol{B}_k = \frac{1}{K_t}\boldsymbol{I} \; \forall k \in \mathcal{K}_t$ and $\sum_{k \in \mathcal{K}_t} \operatorname{tr}(\boldsymbol{B}_k\boldsymbol{R}_k) = 1$ we have $\operatorname{tr}(\boldsymbol{B}_k\boldsymbol{R}_k) = \frac{1}{K_t} \; \forall k \in \mathcal{K}_t$, which means $\operatorname{tr}(\boldsymbol{R}_k) = 1 \; \forall k \in \mathcal{K}_t$.

The orthogonal subspace $\mathcal{Y}$ can be identified as all matrices $(\mu_k\boldsymbol{I} : k \in \mathcal{K}_t)$, such that $\sum_{k \in \mathcal{K}_t} \mu_k = 0$. Without detailed discussion, we assume a problem structure such that the least favorable noise covariances are full rank. According to [10], the least favorable noise covariances are the Lagrangian multipliers for the constraints

$$\boldsymbol{\Sigma}_k \preceq \boldsymbol{B}_k + \boldsymbol{Y}_k \; \forall k \in \mathcal{K}_t.$$

Therefore these constraints will be binding with equality, which yields

$$\boldsymbol{\Sigma}_k = \boldsymbol{B}_k + \boldsymbol{Y}_k = \frac{1}{K_t}\boldsymbol{I} + \mu_k\boldsymbol{I}$$

This means that all uplink transmit covariances are white. Furthermore, we have $\sum_{k \in \mathcal{K}_t} \operatorname{tr}(\boldsymbol{\Sigma}_k) = 1$ and we obtain the following uplink problem:

$$\max_{\mathcal{S}_t} \left\{ \sum_{k \in \mathcal{K}_t} w_k r_k(\mathcal{S}_t, \frac{1}{P}\boldsymbol{I}) : \boldsymbol{\Sigma}_k = P_k\boldsymbol{I}, P_k \geq 0 \forall k, \sum_{k \in \mathcal{K}_t} P_k = 1 \right\},$$

which can be reformulated as

$$\max_{\mathcal{S}_t} \left\{ \sum_{k \in \mathcal{K}_t} w_k r_k(\mathcal{S}_t, \boldsymbol{I}) : \boldsymbol{\Sigma}_k = 1P_k\boldsymbol{I}, P_k \geq 0 \forall k, \sum_{k \in \mathcal{K}_t} P_k = P \right\}.$$

3.2. Shaping Constraint

Our second approach is to reduce the uncertainty in the interference by imposing a shaping constraint on the sum transmit covariance, that is $\boldsymbol{Q}_t \preceq \boldsymbol{C}$, where $\boldsymbol{C}$ is a design parameter. A reasonable choice is for example $\boldsymbol{C} = \frac{P}{N_{\text{tx}}}\boldsymbol{I}$, which we use in this work. This allows for a less pessimistic approximation of the interference, especially if knowledge on the interfering channels is available at the receiver. In case the channel state information is error free and all basestations fully exploit the constraint $\boldsymbol{Q}_t \preceq \frac{P}{N_{\text{tx}}}\boldsymbol{I}$, the prediction by (3) is correct. Although the shaping constraint reduces the set of allowed transmit covariances, we still keep the so much desired abilities for coordination of intra-cell interference by adaptive MIMO transmission, allowing us to serve multiple users on the same resource or multiple streams per user. The noise covariances are computed by (3) and the downlink problem with shaping constraint is

$$\max_{\mathcal{Q}_t} \left\{ \sum_{k \in \mathcal{K}_t} w_k r_k(\mathcal{Q}_t, \boldsymbol{R}_k) : \boldsymbol{Q}_t \preceq \frac{P}{N_{\text{tx}}} \boldsymbol{I} \right\}. \qquad (9)$$

Let $\mathcal{Y}^\perp$ be all K_t-tuples of matrices $(\mu \boldsymbol{R}_k : k \in \mathcal{K}_t)$. By selecting $\boldsymbol{B}_k = \boldsymbol{I}\ \forall k$ and $\sum_{k \in \mathcal{K}_t} \operatorname{tr}(\boldsymbol{B}_k \boldsymbol{R}_k) = 1$, we must have $\mu = 1$ and the least favorable noise covariances are fixed to $(\boldsymbol{R}_k : k \in \mathcal{K}_t)$. The orthogonal subspace $\mathcal{Y}$ implies that $(\boldsymbol{Y}_k : k \in \mathcal{K}_t)$ can be freely chosen, only constraint by $\sum_{k \in \mathcal{K}_t} \operatorname{tr}(\boldsymbol{R}_k \boldsymbol{Y}_k) = 0$. Further, we have $\boldsymbol{B}_k = \boldsymbol{I}$ and $\boldsymbol{\Sigma}_k \preceq \boldsymbol{B}_k + \boldsymbol{Y}_k$, which is equivalent to the constraint $\operatorname{tr}(\boldsymbol{R}_k \boldsymbol{\Sigma}_k) = 1$. By using effective channels $\bar{\boldsymbol{H}}_k = \boldsymbol{R}_k^{-1/2} \boldsymbol{H}_k$ this constraint becomes a sum power constraint on the uplink transmit covariances, i. e., $\sum_{k \in \mathcal{K}_t} \operatorname{tr}(\boldsymbol{\Sigma}_k) = 1$.

The downlink problem with shaping constraint (9) directly admits the structure in (5). We identify $\mathcal{Z} = \{\boldsymbol{0}\}$ and $\mathcal{Z}^\perp = \mathbb{C}^{N_{\text{tx}} \times N_{\text{tx}}}$. As $\boldsymbol{C} = \frac{P}{N_{\text{tx}}} \boldsymbol{I}$, we have $\operatorname{tr}(\boldsymbol{\Omega}_t) = \frac{1}{P}$. This gives us the uplink minimax problem

$$\min_{\boldsymbol{\Omega}_t, \operatorname{tr}(\boldsymbol{\Omega}_t) = \frac{1}{P}} \left\{ \max_{\mathcal{S}_t} \left\{ \sum_{k \in \mathcal{K}_t} w_k r_k(\mathcal{S}_t, \boldsymbol{\Omega}_t) : \sum_{k \in \mathcal{K}_t} \operatorname{tr}(\boldsymbol{\Sigma}_k) = 1 \right\} \right\},$$

which can be reformulated as

$$\min_{\boldsymbol{\Omega}_t, \operatorname{tr}(\boldsymbol{\Omega}_t) = 1} \left\{ \max_{\mathcal{S}_t} \left\{ \sum_{k \in \mathcal{K}_t} w_k r_k(\mathcal{S}_t, \boldsymbol{\Omega}_t) : \sum_{k \in \mathcal{K}_t} \operatorname{tr}(\boldsymbol{\Sigma}_k) = P \right\} \right\},$$

The minimax uplink problem for the shaping constraint transmit covariance method can be formulated such that the solution is a saddle point of a function, which is convex in the noise $\boldsymbol{\Omega}_t$ and concave in the transmit covariances $\mathcal{S}_t$. This allows for efficient algorithms to compute a solution. Both, the least favorable noise and the set of uplink covariances can be freely chosen under a sum-power constraint.

3.3. Interpretation

The two approaches share an interesting symmetry; while the worst case interference approach is a minimax problem with power constraints in the downlink it becomes a pure maximization in the uplink. The shaping constraint approach in turn is a pure maximization problem in the downlink, while the corresponding uplink problem is a minimax problem.

For the worst case noise technique, both the noise covariances and the transmission matrices can be freely chosen, only subject to a power constraint. In the associated uplink problem, this leaves a power allocation as the only degree of freedom for the transmit covariances.

For the constrained transmit covariance problem we observe the opposite, for given noise covariances and a shaping constraint on the sum-transmit covariance, we obtain an uplink problem with arbitrary uplink noise and arbitrary transmit covariances, subject up to power constraints.

3.4. Cross Channel Measurement and Feedback

Clearly, for the worst case noise approximation, we do not rely on cross channel CSI at the transmitter, but it may be used at the receiver to compute the worst case power constant σ_k^2, for example by (7). Still, no additional feedback is required as the constant σ_k^2 can be implicitly considered by feedback of an effective channel $\bar{\boldsymbol{H}}_k = \frac{1}{\sigma_k} \boldsymbol{H}_k$. A disadvantage of the worst approximation is that it usually is way too pessimistic, as the worst case noise for all receivers may be impossible to realize by the interfering transmitters. As an improvement one could explicitly model the feasible noise covariances by considering the cross channels and power constraints on the interfering transmitters, for example by a straight forward extension of [6]. This would however require cross channel CSI at the transmitter, which should allow for more advanced interference coordination methods. For the shaping constraint approach, the interference plus noise matrix can be predicted at the receiver, for example by (3) if the cross-channels are known. By considering effective channels $\bar{\boldsymbol{H}}_k = \boldsymbol{R}_k^{-1/2} \boldsymbol{H}_k$ no additional feedback is needed. Correctly knowing the interference in advance is not only a big advantage for rate allocation, but also avoids algorithmic impairments in higher layer mechanisms such as the resource allocation for fractional reuse. Indeed one of the main drawbacks in the scheme presented in [3] is the non-robust interference prediction, which can be avoided by using one of the robust methods presented here.

3.5. Numerical Simulations

For numerical simulations we consider a scenario with two transmitters that serve two users each. Every user has two receive antennas and the transmitters are equipped with four transmit antennas. To evaluate the performance, we average over multiple realizations of complex Gaussian i.i.d channels and regard the average sum spectral efficiency. As a reference we use the approach based on interference prediction. Contrary to the robust approaches, for the interference prediction approach the rates computed under the prediction can not be guaranteed and we set the rate to zero in case the achievable rate for the true interference is lower than expected (outage). From the results in Figure 1, we can see that the shaping constraint approach outperforms the interference prediction approach for high transmit power, as it can avoid outages by being robust to uncertainty in the interference. Although the worst case approach is robust, its performance is not competitive; the worst assumption seams to be over pessimistic.

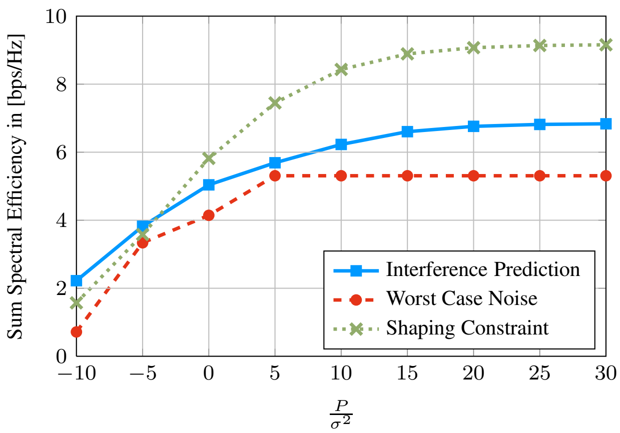

Fig. 1. Simulation Results

4. CONCLUSIONS AND OUTLOOK

In this work, we derived two methods to compute robust downlink transmission strategies. Either the unknown interference is considered by a worst case approximation, or the uncertainty is reduced by limiting the set of allowed transmit covariances. As a result interference can be better predicted in the neighboring cells. For both methods, we can state an equivalent uplink problem, that allows to compute the optimal solution efficiently. To the best of our knowledge, these approaches have not been previously suggested for multi-user transmission. The worst case noise approach extends existing results for point-to-point links to multi-user systems, while the shaping constraint approach generalizes the uplink-downlink duality with multiple trace constraints to a general conic constraint.

The presented algorithms are not applicable for deployable networks, due to the high complexity of dirty paper coding and as the algorithms to find the solutions may not allow for real time implementation. Still, the simulation results indicate that a shaping constraint on the downlink transmit covariance has the potential to increase robustness and performance. This motivates to find less complex methods that are actually implementable, where the insights obtained in this work might be helpful.

As a possible new direction, one could investigate approaches that are between the two extremes presented here, for example where the interference is known to be from a certain subspace, which could be enforced by an artificial constraint. Thus, our result could be extended to new applications in the field of robust transmission strategies or cognitive radio networks.

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