JOINT MULTIUSER DOWNLINK BEAMFORMING AND ADMISSION CONTROL: A SEMIDEFINITE RELAXATION APPROACH

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ABSTRACT

Multiuser downlink beamforming under quality of service (QoS) constraints has attracted considerable interest in recent years, because it is particularly appealing from a network operator's perspective (e.g., UMTS, 802.16e). When there are many co-channel users and/or the service constraints are stringent, the problem becomes infeasible and some form of admission control is necessary. We advocate a cross-layer approach to joint multiuser transmit beamforming and admission control, aiming to maximize the number of users that can be served at their desired QoS. The core problem is NP-hard, yet amenable to convex approximation tools. We propose a computationally efficient semidefinite relaxation algorithm which works remarkably well in a range of experiments, using both simulated and measured channel data.

Keywords: Downlink beamforming, admission control, scheduling, convex approximation, semidefinite relaxation

1. INTRODUCTION

Consider a single transmitter with N antenna elements and K receivers, each with a single antenna. Let $\mathbf{h}_k$ denote the $N \times 1$ complex vector that models the propagation loss and phase shift of the frequency-flat quasi-static channel from each transmit antenna to receiver k, and $\mathbf{w}_k^H$ denote the $1 \times N$ weight vector used to beamform towards receiver (user) k, $k \in \{1, \cdots, K\}$. The following joint multiuser transmit beamforming problem under individual Signal to Interference plus Noise Ratio (SINR) constraints as Quality of Service (QoS) metric has been considered in [4], and [1]:

$$\min_{\{\mathbf{w}_k \in \mathbb{C}^N\}_{k=1}^K} \sum_{k=1}^K ||\mathbf{w}_k||_2^2 \tag{1}$$

$$\text{subject to}: \frac{|\mathbf{w}_k^H \mathbf{h}_k|^2}{\sum_{\ell \neq k} |\mathbf{w}_\ell^H \mathbf{h}_k|^2 + \sigma_k^2} \geq c_k, \ \forall k \in \{1, \cdots, K\}, \tag{2}$$

where σ_k^2 is the additive noise power at receiver k. As shown in [1] (see also [4]), the problem in (1)-(2) is convex (in fact, a *second-order cone program* - SOCP); it can be efficiently solved using modern interior-point methods [7], or specialized iterative algorithms [4]. It is of interest in 3-G systems employing transmit antenna arrays, such as UMTS, but also in the context of QoS-oriented fixed wireless back-haul solutions, such as 802.16e. The main difficulty with the formulation in (1)-(2) is that the problem can easily become infeasible, e.g., when the channel vectors of two or more users are co-linear or highly correlated, and/or the SINR targets are too high, or simply when the number of users, K, is much larger than the number of antennas N - which is the typical scenario in practice. In such a situation, interior point solutions provide an *infeasibility certificate*, whereas the custom-made algorithm in [4] diverges. Either way, infeasibility implies that some users should be dropped (admission control) or rescheduled in orthogonal dimensions (time, frequency, code slot); or the SINR targets should be relaxed.

If users must be dropped / rescheduled, it makes sense to maximize the number of users that can be served at their desired QoS. A brute-force way of doing this is enumeration, each time solving a convex problem for a subset of users. This has prohibitive complexity for all practical purposes. A greedy low-complexity algorithm for admitting a new user was recently proposed in [3]. In order to keep complexity low, [3] advocates fixing the beampatterns of previously admitted users, and jointly optimizing the beampattern of the new user along with power control. Here we seek a better way of solving the problem of joint transmit beamforming and admission control to maximize the total number of users that can be served in the same slot at their desired QoS.

2. MAXIMIZING USER CAPACITY

In the following, we say that a user is *served* if the user is scheduled and its QoS target is supported. Towards this end, we consider the following problem formulation:

$$\min_{\{\mathbf{w}_k \in \mathbb{C}^N, s_k \in \{-1,+1\}\}_{k=1}^K} \epsilon \sum_{k=1}^K ||\mathbf{w}_k||_2^2 + (1-\epsilon) \sum_{k=1}^K \lambda_k (s_k+1)^2 \tag{3}$$

$$\text{subject to}: \sum_{k=1}^K ||\mathbf{w}_k||_2^2 \leq P, \tag{4}$$

$$\frac{|\mathbf{w}_k^H \mathbf{h}_k|^2 + \delta^{-1}(s_k+1)^2}{\sum_{\ell \neq k} |\mathbf{w}_\ell^H \mathbf{h}_k|^2 + \sigma_k^2} \geq c_k, \ \forall k \in \{1, \cdots, K\} \tag{5}$$

Here, the $\lambda_k > 0$ denote normalized weights[1], and ϵ, δ are suitably small positive constants. In particular, we take

$$\delta \leq \min_k \frac{4c_k^{-1}}{P \max_m ||\mathbf{h}_m||_2^2 + \sigma_k^2},$$

which ensures (cf. the Cauchy-Schwartz inequality) that the constraint in (5) is satisfied when $s_k = +1$ even for $\mathbf{w}_k = \mathbf{0}_{N \times 1}$ and irrespective of the other $\mathbf{w}_\ell$, $\ell \neq k$. Since $\min_k \frac{4c_k^{-1}}{P \max_m ||\mathbf{h}_m||_2^2 + \sigma_k^2} \leq$

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[1] E.g., $\lambda_k \sim$ queue length of user k, $\sum_k \lambda_k = 1$.

$\min_k \frac{4c_k^{-1}}{\sigma_k^2}$, this choice of δ also implies that $\mathbf{w}_k = \mathbf{0}_{N\times 1}$, $s_k = 1$, $\forall k$, is always admissible, i.e., the problem in (3)-(5) is always feasible. We also select $\epsilon < \frac{\min_k \lambda_k}{P/4+\min_k \lambda_k}$, which ensures that a user is not dropped unless it is necessary.

The binary slack / scheduling variables s_k play a key role: with $\{\check{\mathbf{w}}_k \in \mathbb{C}^N, \check{s}_k \in \{-1,+1\}\}_{k=1}^K$ denoting an optimal solution of (3)-(5), it is easy to see that $\check{s}_k = -1$ implies that user k is served, whereas $\check{s}_k = +1$ implies that user k is dropped: $\check{\mathbf{w}}_k = \mathbf{0}_{N\times 1}$. This comes from the choice of δ and the cost function, and it also means that there is no need to explicitly account for dropped users in the denominator of (5)).

3. A SEMIDEFINITE RELAXATION APPROACH

It can be shown that the problem in (3)-(5) is NP-hard. The interest in the formulation in (3)-(5), however, stems from its suitability for the application of Lagrangian relaxation tools. In particular, note that

$$(s_k+1)^2 = \left([s_k \quad 1]\begin{bmatrix}1\\1\end{bmatrix}\right)^2 =$$

$$\mathrm{Tr}\left(\begin{bmatrix}1 & 1\\1 & 1\end{bmatrix}\begin{bmatrix}s_k\\1\end{bmatrix}[s_k \quad 1]\right) = \mathrm{Tr}\left(\mathbf{1}_{2\times 2}\mathbf{S}_k\right),$$

with $\mathbf{S}_k := \mathbf{s}_k\mathbf{s}_k^T$, where $\mathbf{s}_k := [s_k \quad 1]^T$. By construction, $\mathbf{S}_k \geq 0$, $\mathrm{rank}(\mathbf{S}_k) = 1$, and $\mathbf{S}_k(2,2) = 1$; if we further insist that $\mathbf{S}_k(1,1) = 1$, then there are only two possibilities for $\mathbf{S}_k$:

$$\mathbf{S}_k = \begin{bmatrix}1 & 1\\1 & 1\end{bmatrix} \rightarrow \mathrm{Tr}\left(\mathbf{1}_{2\times 2}\mathbf{S}_k\right) = 4; \quad or$$

$$\mathbf{S}_k = \begin{bmatrix}1 & -1\\-1 & 1\end{bmatrix} \rightarrow \mathrm{Tr}\left(\mathbf{1}_{2\times 2}\mathbf{S}_k\right) = 0.$$

As a result, the scalar binary variables s_k can be replaced by the 2×2 real matrix variables $\mathbf{S}_k$, and the ± 1 constraints can be replaced by positive semidefinite, rank-one, and linear equality constraints[2]. Of the latter, only the rank-one constraint is non-convex, and thus difficult to handle.

In the same spirit, we may define rank-one positive semidefinite matrix variables $\mathbf{W}_k := \mathbf{w}_k\mathbf{w}_k^H$, and $\mathbf{H}_k := \mathbf{h}_k\mathbf{h}_k^H$, and rewrite the optimization problem in (3)-(5) equivalently as

$$\min_{\{\mathbf{W}_k\in\mathbb{C}^{N\times N}, \mathbf{S}_k\in\mathbb{R}^{2\times 2}\}_{k=1}^K} \epsilon\sum_{k=1}^K \mathrm{Tr}(\mathbf{W}_k) + (1-\epsilon)\sum_{k=1}^K \lambda_k \mathrm{Tr}(\mathbf{1}_{2\times 2}\mathbf{S}_k) \tag{6}$$

$$\text{subject to}: \sum_{k=1}^K \mathrm{Tr}(\mathbf{W}_k) \leq P, \tag{7}$$

$$\frac{\mathrm{Tr}(\mathbf{H}_k\mathbf{W}_k) + \delta^{-1}\mathrm{Tr}(\mathbf{1}_{2\times 2}\mathbf{S}_k)}{\sum_{\ell\neq k}\mathrm{Tr}(\mathbf{H}_k\mathbf{W}_\ell) + \sigma_k^2} \geq c_k, \ \forall k, \tag{8}$$

$$\mathbf{W}_k \geq 0, \mathrm{rank}(\mathbf{W}_k) = 1, \ \forall k, \tag{9}$$

$$\mathbf{S}_k \geq 0, \mathrm{rank}(\mathbf{S}_k) = 1, \mathbf{S}_k(1,1) = \mathbf{S}_k(2,2) = 1, \ \forall k. \tag{10}$$

Dropping the rank-one constraints[3], we obtain the following convex relaxation of (6)-(10):

$$\min_{\{\mathbf{W}_k\in\mathbb{C}^{N\times N}, \mathbf{S}_k\in\mathbb{R}^{2\times 2}\}_{k=1}^K} \epsilon\sum_{k=1}^K \mathrm{Tr}(\mathbf{W}_k) + (1-\epsilon)\sum_{k=1}^K \lambda_k \mathrm{Tr}(\mathbf{1}_{2\times 2}\mathbf{S}_k) \tag{11}$$

[2]This is another incarnation of the basic trick in [6].

[3]Problem (6)-(10) is a quadratically constrained quadratic program, and rank relaxation can be interpreted as its bi-dual problem [10], which further motivates rank relaxation from a Lagrangian perspective.

$$\text{subject to}: \sum_{k=1}^K \mathrm{Tr}(\mathbf{W}_k) \leq P, \tag{12}$$

$$\mathrm{Tr}(\mathbf{H}_k\mathbf{W}_k) + \delta^{-1}\mathrm{Tr}(\mathbf{1}_{2\times 2}\mathbf{S}_k) \geq c_k\sum_{\ell\neq k}\mathrm{Tr}(\mathbf{H}_k\mathbf{W}_\ell) + \sigma_k^2, \ \forall k, \tag{13}$$

$$\mathbf{W}_k \geq 0, \ \forall k, \tag{14}$$

$$\mathbf{S}_k \geq 0, \mathbf{S}_k(1,1) = \mathbf{S}_k(2,2) = 1, \ \forall k, \tag{15}$$

where we have also used the fact that the denominator in (8) is positive. The problem in (11)-(15) is a semidefinite program, which can be efficiently solved using modern interior point solvers such as SeDuMi [7]. Being a relaxation of (3)-(5), the problem in (11)-(15) is always feasible, provided that the constants ϵ, δ are chosen as suggested earlier.

It is interesting to recall that rank relaxation of the matrices $\mathbf{W}_k$ for the original problem (without user selection) is not a relaxation after all, as shown in [1]. It is also interesting to note that the matrices $\mathbf{S}_k$ are of rank at most two, hence the associated rank relaxation step is far milder than usual. In particular, the following can be shown by direct examination of eigenvalues:

Property 1 *Consider a real symmetric positive semidefinite matrix with diagonal elements equal to one, i.e.,*

$$\mathbf{S} = \begin{bmatrix}1 & x\\x & 1\end{bmatrix} \geq \mathbf{0}.$$

Then rank$(\mathbf{S}) = 1 \Longleftrightarrow x \in \{-1,+1\}$, *whereas rank*$(\mathbf{S}) \in \{1,2\} \Longleftrightarrow x \in [-1,+1]$.

Thus rank relaxation of $\mathbf{S}_k$ amounts to relaxing the $\{-1,+1\}$ constraint on its off-diagonal element to a $[-1,+1]$ interval constraint. The associated penalty (sum of elements) is always non-negative, in $[0,4]$. These observations suggest that (11)-(15) is a relatively tight relaxation of (6)-(10).

Gaussian randomization coupled with multiuser power control (MPC) can be used to convert the optimal solution of (11)-(15) into an approximate solution of (6)-(10); e.g., see related approaches in [8, 9]. As an alternative to randomization / MPC, we may proceed as follows. The difficult part of the problem is the determination of which users to drop. Once this part is solved, the rest is SOCP. One idea is to try to determine this from the solution of the relaxed problem, by examining the 2×2 matrix variables $\mathbf{S}_k$, and/or the optimum of the cost function itself. For example, the optimum value can yield an upper bound on the maximum number of admissible users. From the various approaches that we tried so far, the following appears to work best in practice:

Algorithm 1

1. *Set* $\mathcal{U} := \{1, ..., K\}$;
2. *Solve problem (11)-(15) for the users in* $\mathcal{U}$. *Let* $\{\check{\mathbf{W}}_k\}_{k\in\mathcal{U}}$ *denote the resulting optimal transmit covariance matrices;*
3. *For each* $k \in \mathcal{U}$, *extract the principal component of* $\check{\mathbf{W}}_k$, *and scale it to power* $Tr(\check{\mathbf{W}}_k)$; *i.e., set* $\check{\mathbf{w}}_k := \sqrt{Tr(\check{\mathbf{W}}_k)}\check{\mathbf{u}}_k$, *where* $\check{\mathbf{u}}_k$ *is the unit-norm principal component of* $\check{\mathbf{W}}_k$.
4. *For each* $k \in \mathcal{U}$, *check whether* $\frac{|\check{\mathbf{w}}_k^H\mathbf{h}_k|^2}{\sum_{\ell\neq k}|\check{\mathbf{w}}_\ell^H\mathbf{h}_k|^2+\sigma_k^2} \geq c_k$ *holds; if so, stop (a feasible solution has been found); else pick the user with largest gap to its target SINR (smallest attained SINR if all the SINR targets are equal), remove from* $\mathcal{U}$, *and go to step 2.*

Our experiments in the following section indicate that the above algorithm works remarkably well, for both simulated and real (measured) channel data.

4. EXPERIMENTS

We conducted experiments using both simulated and measured channel data. In both cases, we used SOCP enumeration (i.e., solving the problem in (1)-(2) using SeDuMi [7] for all possible user combinations) as a baseline for comparison. SOCP enumeration provides the optimum solution(s), but its complexity grows combinatorially. The maximum problem size that we could solve this way was $K = 18$ users, requiring over 7 hours of computation. In all experiments, the number of transmit antennas is set to $N = 4$.

• Simulated Rayleigh channel data: The first suite of experiments employed simulated i.i.d. complex normal zero-mean, unit-variance ($\mathcal{CN}(0, 1)$) channel gains. The results are reported in Table 1, grouped according to target SINR. SOCP enumeration can be programmed to return all feasible solutions that serve the maximum possible number of users. One of them is optimum in the sense of requiring the smallest transmit power, but it is useful to know other possibilities as well, for comparison purposes. By definition, our reduced complexity algorithm always returns one solution. Simulation parameters are grouped together in the associated caption, for ease of reference. In all cases considered, our algorithm is able to serve the maximum possible number of users at the desired SINR, at a power budget that is close to optimum in most cases, and about 3 dB away from optimum in the worst case. This is very encouraging, given that our algorithm only takes a few seconds to run.

• Measured channel data: The performance of the proposed algorithm was also tested on measured channel data downloaded from the iCORE HCDC Lab web site (http://www.ece.ualberta.ca/∼mimo/), University of Alberta in Edmonton (see also [5]). The site contains detailed descriptions of numerous measurement campaigns in the 902–928 MHz (ISM) band. The most pertinent scenario for our purposes is the stationary outdoor one, called Quad and illustrated in Figure 1. Quad is a 150 by 60 meters lawn surrounded by buildings with heights ranging from 15 to 30 meters. The transmitter (Tx) location was fixed while the receiver (Rx) was placed in 6 different locations (no measurements are actually provided for location 4). Both Tx and Rx were equipped with antenna arrays, each comprising four vertically polarized dipoles spaced $\lambda/2$ ($\approx$ 16 cm) apart. The channels are frequency-flat, slowly time-selective fading, due to pedestrian movement and other factors (the chip rate used for sounding was low enough to safely assume that the channels are not frequency selective). For every Rx location, 9 different measurements were taken by shifting the Rx antenna array on a 3×3 square grid with $\lambda/4$ spacing. Each measurement contains about 100 4×4 channel snapshots, recorded 3 per second. We assumed a total of $K = 18$ single-antenna downlink users, placed in 6 groups on 3 outermost corners of each active Rx location, as shown in Figure 1. We report results for a single channel snapshot (due to the complexity of the enumeration-based algorithm that is used as a benchmark), but note that the channels are only mildly fading, and qualitative results are similar for other snapshots as well. For ease of comparison with the simulated Rayleigh case, channel gains were normalized before use, dividing by the average channel amplitude for the respective configuration. The results are reported in Table 2. Note that the proposed algorithm again serves the maximum possible number of users in all cases considered, and is closer to the optimum in terms of the associated transmit power than in the case of simulated channels.

5. CONCLUSIONS

We have presented a computationally efficient joint multiuser transmit beamforming and admission control algorithm. The objective is to maximize the number of users that can be supported at their desired SINR, which is appealing from a network operator's perspective. The core problem is NP-hard, yet we have shown that it is well-suited to convex approximation (in particular, semidefinite relaxation) tools. For a moderate user population, our experiments with simulated and measured channel data indicate that the proposed algorithm yields high-quality feasible solutions at a low computational cost.

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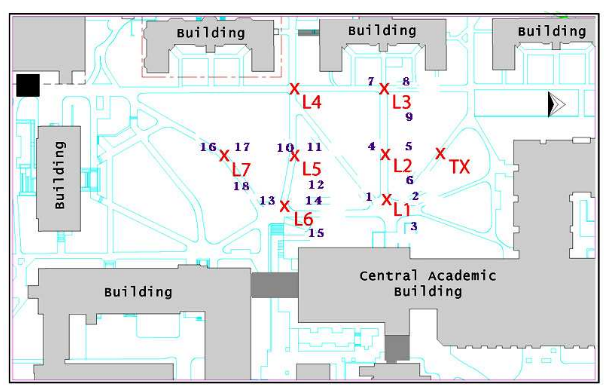

Fig. 1. Sample wireless channel measurement scenario from http://www.ece.ualberta.ca/∼mimo/

Table 1. Simulation results (i.i.d. Rayleigh $\mathcal{CN}(0,1)$): $N = 4$ Tx Ant., $K = 18$ users, $P = 100$; $\sigma_k^2 = \sigma^2 = 1$, $c_k = c$, $\lambda_k = 1, \forall k$; $e = 0.0001 < \frac{1}{P/4+1}$, $\delta = \frac{4c^{-1}}{P \max_m ||\mathbf{h}_m||_2^2+\sigma^2}$.

	SOCP enum	Proposed
SINR	3 dB	3 dB
♯ users served	5	5
Users served	2,6,8,13,16	7,8,10,13,16
Tx Power	6.6	8.4
Users served	2,8,9,13,16	-
Tx Power	6.6	-
Users served	2,4,6,8,11	-
Tx Power	6.8	-
Users served	4,7,8,10,13	-
Tx Power	7.0	-
Users served	1,7,8,9,11	-
Tx Power	7.0	-
Time	7.46h	2.463 sec
SINR	5 dB	5 dB
♯ users served	5	5
Users served	2,8,9,13,16	7,8,10,13,16
Tx Power	27.2	53.8
Users served	1,7,8,9,11	-
Tx Power	28.1	-
Users served	2,6,8,13,16	-
Tx Power	28.7	-
Users served	1,7,8,9,16	-
Tx Power	28.9	-
Users served	2,4,6,8,11	-
Tx Power	29.7	-
Time	7.49 h	2.2064 sec
SINR	10 dB	10 dB
♯ users served	4	4
Users served	7,8,10,11	7,8,10,13
Tx Power	12.8	13.9
Users served	2,6,8,11	-
Tx Power	12.9	-
Users served	7,8,10,13	-
Tx Power	13.9	-
Users served	6,8,11,17	-
Tx Power	14.1	-
Users served	2,6,8,16	-
Tx Power	14.5	-
Time	7.53 h	2.3024 sec
SINR	15 dB	15 dB
♯ users served	4	4
Users served	7,8,10,11	2,8,13,16
Tx Power	41.3	57.3
Users served	2,6,8,11	-
Tx Power	41.7	-
Users served	7,8,10,13	-
Tx Power	45.0	-
Users served	6,8,11,17	-
Tx Power	45.4	-
Time	7.55 h	2.262 sec

Table 2. Simulation results (measured channels): $N = 4$ Tx Ant., $K = 18$ users, $P = 100$; $\sigma_k^2 = \sigma^2 = 1$, $c_k = c$, $\lambda_k = 1, \forall k$; $e = 0.0001 < \frac{1}{P/4+1}$, $\delta = \frac{4c^{-1}}{P \max_m ||\mathbf{h}_m||_2^2+\sigma^2}$.

	SOCP enum	Proposed
SINR	3 dB	3 dB
♯ users served	5	5
Users served	5,11,13,15,16	5,11,13,15,16
Tx Power	7.3	7.3
Users served	5,11,14,15,16	-
Tx Power	7.3	-
Users served	9,11,13,15,16	-
Tx Power	7.6	-
Users served	9,11,14,15,16	-
Tx Power	8.1	-
Users served	4,11,13,15,16	-
Tx Power	8.1	-
Time	7.52h	2.5563 sec
SINR	5 dB	5 dB
♯ users served	5	5
Users served	5,11,13,15,16	5,11,13,15,16
Tx Power	31.1	31.1
Users served	5,11,14,15,16	-
Tx Power	31.8	-
Users served	4,11,13,15,16	-
Tx Power	34.8	-
Users served	4,11,14,15,16	-
Tx Power	36.2	-
Users served	9,11,13,15,16	-
Tx Power	36.2	-
Time	7.48 h	2.3552 sec
SINR	10 dB	10 dB
♯ users served	4	4
Users served	11,14,15,16	11,13,15,16
Tx Power	17.5	18.4
Users served	11,13,15,16	-
Tx Power	18.4	-
Users served	2,5,14,18	-
Tx Power	18.5	-
Users served	1,5,14,18	-
Tx Power	18.6	-
Users served	2,5,13,18	-
Tx Power	19.1	-
Time	7.58 h	2.3724 sec
SINR	15 dB	15 dB
♯ users served	4	4
Users served	11,14,15,16	11,13,15,16
Tx Power	58.0	61.1
Users served	2,5,14,18	-
Tx Power	60.9	-
Users served	11,13,15,16	-
Tx Power	61.1	-
Users served	1,5,14,18	-
Tx Power	61.3	-
Time	7.585 h	2.397 sec