COORDINATED MIMO TRANSMISSION FOR MULTI-USER INTERFERENCE NULLING WITH SIMPLE RECEIVER CONSTRAINT

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ABSTRACT
Smart antennas, and in particular MIMO technologies, have been proven to provide large capacity increases in dispersive propagating scenarios [1,2]. We investigate how capacity is affected in a many-to-one multiuser scenario if the transmitters are designed jointly so as to completely cancel the multiuser interference at the receiver and, at the same time, maximise the received signal power. The receiver is constrained to be a simple matched filter. Equations for the determination of the optimum are derived and outage capacity figures compared for different number of transmit antennas. Results show that the loss in capacity is low when the number of transmit-receive antennas is moderate, and the main gain is obtained in receiver complexity.

1. INTRODUCTION
With the advent of broadband wireless access at high bit rates, architectures evolve towards the interconnection of heterogeneous systems in which WLAN standards are to play an important role, as giving coverage beyond the capacities of 3G systems. On the other hand, the higher bandwidth thought of for these systems (around 100 MHz) is devised along with by a higher carrier frequency. The higher attenuation suffered at high frequencies lead the systems designers to uneconomical solutions in which the spatial density of access points (AP) grows high resulting in systems in which payload per unit area grows beyond the users needs.

As a result, multihop networks are arising as a feasible solution to extend the coverage of those AP. The implicit assumption behind those networks is that those terminals which are far from (probably out of the coverage of) the AP may reach it through a closer relay terminal, thus reducing the power needs and increasing the effective throughput.

On the other hand, the use of multiple links to establish a connection seems to be against the principle of economy. Gains in multihop networks arise from the splitting of the propagation losses through multiple links and from the use of more advantageous propagating conditions (i.e. LOS vs NLOS situations) in such a way that the total energy per transmitted bit from the source to the destination is lower if the connection is split in multiple links.

In addition to that, the concept of spatial reuse of the physical resources is of the greatest importance to improve the system capacity. Spatial reuse may be dealt in multiple ways and at multiple levels. Using a centralised strategy, radio resource management in cellular systems assumes the existence of a central controller which cares about the spatial interference. In a more distributed approach, spatial reuse may be dealt at the physical and MAC layers by trying to avoid or cancel uncoordinated interferences.

In the approach taken here, spatial multiplexing among users will be analysed as a possibility for channel reuse in many-to-one communication. Spatial multiplexing (often called as SDMA) has been paid a lot of attention in the past mainly through interference cancellation of users reaching an antenna with different spatial signatures, both for 2G and 3G systems, for UL in communications many-to-one. In the DL, that is in communications one-to-many, spatial multiplexing may be achieved also by assuming different spatial signatures of the mobile terminals and by focusing the antenna elements of the BS to maximise the SNR at the terminals [3]. Previous approaches for the coordination of multiple users in many-to-one communications for efficient dispersive channel usage may be found in [5], but the approach taken there implies notification between cooperative users of the symbols to be transmitted, which is not assumed here.

The paper is organised as follows: section 2 describes the problem and proposes a solution for the two users case for an arbitrary number of antennas at the AP and the terminal.
An inductive path for a solution in more than two users case is proposed in section 3. Figures of capacity may be found in section 4. Concluding remarks are found in section 5.

2. TWO USERS OPTIMISATION

It will be assumed that multiple users want to transmit to a single one and that multiple antennas are used both at the transmitter and at the receiver. It will be assumed that OFDM is used, so the wideband receiver will be formed by a number of narrowband simple spatial matched filters. Uncoordinated interference is taken into account in the receiver through spatial whitening assuming that the interference correlation matrix $R_w$ is known. The transmitter will be also as simple as possible and will consist of a simple spatial combiner. The objective is to co-ordinate the transmission from the multiple terminals so as to eliminate the MUI, understood as cross-over among users, at the receiver. It will be shown that, provided that as the scattering of the channel is sufficiently rich, the available degrees of freedom allow interference cancellation and capacity losses per user with respect to a single user transmission are negligible.

In order to simplify the derivation, let us assume a system as in Figure 1. The channel matrix $H_i$ contains the spatio-temporal matrix between the $M$ transmitting antennas and the $N$ receiving antennas. Assume that the spatial combiners associated to users 1 and 2 are denoted as $b_1$ and $b_2$. As mentioned, the receiver at the sink terminal is a spatial matched filter, which for user 1 is formulated as $v_1 = R_w^{-1}H_1b_1$. This differs from other approaches (as in [4]) where transmitters and receivers are jointly optimised for some objective function related to BER.

In the reception of user 1, the influence of user 2 is to be cancelled and vice-versa. The beamformers may be designed so as the total received power is maximised. In this way, the design equations for the receivers $b_1$ and $b_2$ may be written as:

$$\max_{b_1, b_2} \ b_1^H \ b_1 + b_2^H \ b_2$$

with the following constraints:

- $b_1^H \ b_1 = 1$
- $b_2^H \ b_2 = 1$
- $b_1^H \ H_1^H R_w^{-3} H_1 b_2 = 0$

The solution to this problem is found by substituting all combinations of left and right orthogonal singular vectors of $S = H_i^H R_i^{-1} H_i$ into (1) and determining the pair achieving the maximum received power. Let us select a set of left singular vectors from matrix $S$ in $U$ and the corresponding orthogonal right singular vectors in $V$. The number of sets of singular vectors that can be selected is $2^M - 2$. The solution for $b$ should be a linear combination of the chosen left singular vectors ($b = U c$). Now, the problem can be reformulated as:

$$\max_{c_1, c_2} \ c_1^H U^H H_1^H R_1^{-1} H_1 U c_1 + c_2^H V^H H_2^H R_2^{-1} H_2 V c_2$$

$$\begin{align*}
&b_1 = U c_1 & c_1^H c_1 = 1 & i = 1, ..., 2^M - 2 \\
&b_2 = V c_2 & c_2^H c_2 = 1 \end{align*}$$

where $U \in \mathbb{C}^{M \times K}$ and $V \in \mathbb{C}^{M \times K}$ with $K = 1, ..., M - 1$.

The solution for vectors $c$ are the eigenvectors associated to the maximum eigenvalues of the corresponding matrices. These have to be computed for every singular vectors set $i$ and the maximum among all is the solution to the problem. The number of SVD involved in the solution grows rapidly with the number of antennas, but the size of the matrices involved is moderate: for $M=2$ the solution implies one single SVD of 2x2; for $M=3$, seven SVD of 2x2 are required; for $M=4$, eight SVD of 3x3 and twelve SVD of 2x2.

This strategy requires that the sink terminal knows the space-time channels involved, computes and transmits the coefficients of the combiners to users 1 and 2. Distributed strategies need to be devised to cope with this situation.
3. MULTIPLE USERS OPTIMISATION

For more than two users, the solution proposed can be easily inferred:

$$\max_{b_1,...,b_n} \sum_{k=1}^{N_u} b_k^H H_k^H R_k H_k b_k$$

with the following constraints:

$$b_k^H b_k = 1 \quad k \in \{1,...,N_u\}$$
$$b_k^H H_k^H R_k H_k b_l = 0 \quad \forall k,l \in \{1,...,N_u\} \cap k \neq l$$

where the number of null constraints is $$\binom{N_u}{2}$$. Since a generic formulation for an arbitrary number of users is too burdensome in notation, the particular case of three users may be found in the appendix and illustrates the methodology. We leave the extension for an arbitrary number to the final paper version.

4. CAPACITY RESULTS

The outage capacity of the proposed scheme is compared to the multiuser channel capacity and to the maximum-received power beamformer of [1], for the two users case. The capacity in all cases is computed according to

$$C = \log_2 \left( \det \left( I + \frac{\text{SNR}}{M} H^H H \right) \right)$$

where the channel matrix takes different forms: for the multiuser unconstrained case $$H = [H_1, H_2]$$ and for the multiuser with beamformer at the transmitter side

$$H = [H_1 b_1, H_2 b_2]$$

It has been assumed 20 dB of SNR and all users transmitting the same total power. The channel is Gaussian and uncorrelated among users.

Figure 2 shows the outage capacity for different number of antennas with the proposed technique and for the MU channel. Differences are sensible and increase with the number of antennas as a result of restricting the number of possible channel modes, as expected. On the other hand, figure 3 compares the proposed approach to the maximum received power beamformer of [1]. Note that differences in capacity are now very much equivalent. Note also a sensible gain in the mean capacity as the number of antennas increases. The benefit obtained is the lower complexity in the receiver as the users are separated by the channel diversity itself.

Figure 2. Outage capacity when coordinated users with MUI nulling (solid), compared to the multiuser channel capacity (dashed), for 2x2, 3x3 and 4x4 MIMO configurations.

Figure 3. Outage capacity when beamformer is used in transmission, assuming coordinated MUI nulling (solid) or maximum received power (dashed), for 2x2, 3x3, 4x4 and 5x5 MIMO configurations.
5. CONCLUSIONS

It has been shown that coordinated transmission with perfect MUI cancellation is possible with very simple matched filter receiver in the framework of MIMO transmission/reception. The objective function taken in this case is the maximisation of the total power received by the two users. It is implicit that the channels associated to the users involved in the transmission have to be sufficiently rich (there is enough spatial diversity). The scheme proposed assumes there exists some feedback mechanism for transferring the optimum weights from the sink terminal to the transmitters. Outage capacity shows losses with respect to multiuser capacity, but comparable performance with respect to maximum received power beamformers \[1\] per user. Extensions of the approach to spread modulations and wideband channels are underway. Sensitivity with respect to channel estimation errors is also a matter for further study.

6. APPENDIX

Let us formulate again by SVDing the null restrictions and proceed by selecting the null left-right subspaces as in the two users case. We will proceed by extracting on each condition and replacing them on the other null constraints equations. Using the first as reference:

\[
b_i^H H_i^H R_i^{-1} H_i b_2 = b_i^H U D V^H b_2 = 0
\]

and replacing these expressions in the remaining null constraint equations:

\[
b_i^H H_i^H R_i^{-1} H_i U c_1 = 0
\]

\[
b_i^H H_i^H R_i^{-1} H_i V c_2 = 0
\]

and replacing these expressions in the remaining null constraint equations:

\[
b_i^H H_i^H R_i^{-1} H_i U c_1 = 0
\]

\[
b_i^H H_i^H R_i^{-1} H_i V c_2 = 0
\]

Let us take the last of the equations and repeat the procedure as in equations (2) and (3):

\[
b_3^H H_3^H R_3^{-1} H_3 V c_2 = b_3^H W A T^H c_2 = 0
\]

\[
b_3^H = W^{i,j,k} c_3 \quad c_i^{j,k} = T^{i,j} d_i
\]

After all these back substitutions, the final optimum set of transmitting vectors is given by the set of vectors associated to the proper \(i, j, k\) partitions of the singular spaces, which maximise:

\[
\max_{d_i^{j,k}} \sum_{i,j,k} d_i^{j,k} A_{i,j,k}^{j,k} d_i
\]

\[
A_{i,j,k}^{j,k} = Z_i^{j,k} H_i^H R_i^{-1} H_i U^{i,j,k}
\]

\[
A_{i,j,k}^{j,k} = T_i^{j,k} H_i^H R_i^{-1} H_i V
\]

\[
A_{i,j,k}^{j,k} = X_i^{j,k} H_i^H R_i^{-1} H_i W^{j,k}
\]

whose solution requires the computation of the maximum eigenvector associated to matrices \(A\). Note that the complexity increases substantially with the number null constraints (that is, of users), as per each subspace selection \((i)\) different multiple subspace selections must be done \((j,k)\).

7. REFERENCES


