A REAL TIME DOWNLINK CHANNEL ALLOCATION SCHEME FOR AN SDMA MOBILE RADIO SYSTEM

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ABSTRACT

In SDMA mobile radio systems where only base stations, but no mobiles are equipped with antenna arrays, co-channel interference on the downlink has to be kept down by beamforming. The performance of the beamformer is determined by the directions of arrival (DOAs) of the users operating in the same frequency/time/code slot. Thus the full capacity of an SDMA cell can only be made use of by an effective channel allocation scheme. In this paper, a real time concept for channel allocation is presented. Furthermore, several criteria to quickly evaluate the spatial separability of subsets of users, were defined and then compared to each other by means of simulations.

1. DATA MODEL

1.1 Channel model

We assume an SDMA mobile radio cell which has L different FTCDMA channels (i.e. frequency, time or code slots or combinations thereof) at its disposal. We also assume there is a maximum number K_c of SDMA users per channel, so that the maximum number of manageable users per cell is $L \cdot K_c$. The channel allocation problem is to find L groups with spatially well separable users under real time conditions.

The base station of the SDMA cell is equipped with an M element antenna array. The distances from all users, reflectors and scatterers to the array are assumed to be much larger than the array spacing, so that all waves reaching the array are planar (far-field approximation). Moreover, the bandwidth of all baseband signals received from (rsp. transmitted to) the users is considered to be much smaller than the reciprocal of the maximum time that a planar radio wave needs to cover the length of the array (narrow-band approximation).

Throughout this paper, vectors are always considered to be column vectors and are denoted by lower case bold faced letters and matrices by upper case bold faced letters. The symbols $(\dots)^H$ and $\|\dots\|_F$ designate the complex conjugate transposition and the Frobenius norm of a matrix or vector.

On the uplink and downlink we consider a discrete direction of arrival channel. The signal produced by the user k reaches the base station through a limited number Q_k of discrete propagation paths. Each path q is characterized by the attenuation factor $A_{k,q}$ and presumed to consist of a high number $R_{k,q}$ of subpaths with equal attenuations. The subpaths are produced by diffractions and scatterings in the close vicinity of the mobile or a dominant reflecting center and have individual phase shifts and Doppler frequencies [1]. However, since they are produced in a comparably small area, they nearly have the same DOA and time delay.

We will consider a mobile radio channel situation of a duration between 100 ms and 10 s, so that the numbers of dominant propagation paths, as well as the corresponding DOAs, do not change. The absolute values of the complex amplitudes of all subpaths are considered constant, whereas their phases are assumed to be samples of rapidly changing independent stochastic processes with equal distribution in the range $]-\pi;\pi]$.

1.2 Useful power and interference power

On the downlink we assume a baseband signal $s_k(t)$ with $E\{|s_k(t)|^2\} = 1$ bound for the user k. Beamforming is done by multiplying the signal $s_k(t)$ at each antenna m by a specific complex factor $w_{k,m}$ before modulation and transmission. The vector $\boldsymbol{w}_k$ containing the M complex factors $w_{k,m}$ will be called a weight vector. The weight vectors of all users in the same channel

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l form the weight matrix $\boldsymbol{W}^{(l)}$.

The DOA of the subpath r corresponding to the path q of the user k is characterized by the steering vector $\boldsymbol{a}_{k,q,r}$. It depends on the azimuth $\psi_{k,q,r}$ and the elevation $\theta_{k,q,r}$ of the wavefront impinging on the array, and incorporates the phase shifts inflicted to the corresponding baseband signal propagating from antenna to antenna. The $M \times M$ spatial covariance matrix $\boldsymbol{C}_k$ of the user k is defined as

$$\boldsymbol{C}_k = \sum_{q=1}^{Q_k} A_{k,q} \cdot R_{k,q}{}^{-1} \sum_{r=1}^{R_{k,q}} \boldsymbol{a}_{k,q,r}\, \boldsymbol{a}_{k,q,r}^H. \qquad (1)$$

For the downlink the expectation $S_{y,z}$ of the signal power received by the user y and created by the weight vector $\boldsymbol{w}_z$ can be easily expressed by means of the spatial covariance matrix as follows:

$$S_{y,z} = \boldsymbol{w}_z^H \boldsymbol{C}_y \boldsymbol{w}_z. \qquad (2)$$

2. THE ALLOCATION SCHEME

The allocation scheme mainly concentrates on the needs of the downlink. We presume that in an SDMA mobile radio system the users receiving in the same FTCDMA channel on the downlink do not necessarily have to be the same as the ones transmitting in the same FTCDMA channel on the uplink.

On the downlink the DOAs are decisive for channel allocation, as users with identical DOAs cannot be separated by beamforming. Joint data detection on the uplink [2] still works although the performance is worse than with users having different DOAs.

On the other hand, the users in the uplink need to be arranged in power classes [3] due to the limited dynamic range of the mobile transmitters.

We will assume an SDMA cell with L different channels having identical properties. At a time when $K^{(l)}$ users in each channel l are managed by SDMA ($K^{(l)} \in [0; K_c]$), a new user k requests for a communication channel. We suppose that his spatial covariance matrix $\boldsymbol{C}_k$ is known, because the base station has the chance to estimate the necessary spatial parameters during the signalling procedure. The matrix $\boldsymbol{C}_k$ can be calculated by means of the mean attenuation factors $A_{k,q}$ and mean steering vectors $\bar{\boldsymbol{a}}_{k,q}$ of the Q_k dominant propagation paths. The estimation of Q_k, the DOAs and the attenuations can be done by direction finding algorithms like those presented in [4], [5] and [6].

If the total number $1 + \sum_{l=1}^{L} K^{(l)}$ of users does not exceed L, the new user can simply be allocated to one of the free channels. Otherwise, a test procedure has to be executed for each channel l with $K^{(l)} < K_c$. This test operating on the spatial covariance matrices of $1 + K^{(l)}$ users will further on be called "spatial separability check", since it is supposed to evaluate how well beamforming can spatially separate a set of users. The best result of the L checks determines the "most suitable" channel l_1 the new user can be allocated to.

By downlink beamforming, the base station has to guarantee a given expectation $SNIR$ of the signal-to-noise-and-interference-ratio for all users in its cell. The electromagnetic power P that has to be emitted by the base station antenna array to meet the SNIRs is highly dependent on the dominant DOAs of the users arranged in each channel. We will define the optimal solution to the channel allocation problem as finding the channel $l_1 \in [1; L]$ causing the smallest increase $\triangle P^{(l)}$ in power after allocating the new user to it. The power increase $\triangle P^{(l)}$ can be calculated by

$$\triangle P^{(l)} = \|\hat{\boldsymbol{W}}^{(l)}\|_F^2 - \|\tilde{\boldsymbol{W}}^{(l)}\|_F^2, \qquad (3)$$

with $\tilde{\boldsymbol{W}}^{(l)}$ and $\hat{\boldsymbol{W}}^{(l)}$ denoting the weight matrices before and after the allocation of the new user. We consider this solution optimal, since in a cellular system minimal emission of electromagnetic power at the base also implies minimal interference in neighboring cells.

For two reasons we will refrain from reallocating any user(s) during the allocation procedure: First to avoid the signalling effort due to the handover procedure(s) and second not to increase the necessary number of separability checks. Otherwise overloading an FTDMA mobile radio cell with 8 TDMA slots in 2 frequency bands ($L = 16$) by a factor $K_c = 2$ could result in a maximum of $(L \cdot K_c)!/(K_c!^L \cdot L!) \approx 2 \cdot 10^{17}$ possible arrangements of users (and checks, respectively).

If the number of users exceeds $L \cdot K_c$, any new user will automatically be rejected. But even with a smaller number of users the following cases have to be considered:

(a) A new user has an extremely homogenious angular power spectrum disqualifying him for the application of SDMA.

(b) A new user's dominant DOA(s) are the dominant ones of too many other users in the same cell.

(c) Using a suboptimal criterion to approximate the spatial separability of users produced a wrong index l_1.

As in practice the allocation of a new user to an unfavorable channel may lead to the complete communication breakdown in that channel, the channel allocation scheme has to be provided with a rejection handling mechanism. We suggest the following procedure:

1. The separability tests yield a tentative "best" channel index l_1.

2. The new weight matrix $\hat{W}^{(l_1)}$ for the $1 + K^{(l_1)}$ users in the optimal channel has to be calculated by executing the full beamforming algorithm.

3. If the power increase $\triangle P^{(l_1)}$ exceeds a certain level $\triangle P_{max}$, the allocation is considered a failure corresponding to the case (c).

4. In case of a failure the steps 2 and 3 are repeated for the second (third $\cdots$) but best channel l_2 ($l_3 \cdots$) until either an allocation is successful or a maximum number of failures f_{max} is reached.

5. If the number of failures equals f_{max}, the new user will be rejected suspecting case (a) or (b).

We suggest to define the failure level $\triangle P_{max}$ mentioned above as the product of a fixed factor r_{max} and the minimal possible power increase that would result from allocating the new user k to a free channel. In that case the optimal weight vector $\hat{w}_k$ would be the solution of the constraint optimization problem

$$\overset{min}{w_k} \{\|w_k\|_F^2\} \ \forall \ w_k : \frac{S_{k,k}}{SNIR} = N_k, \tag{4}$$

with N_k designating the noise relevant for the receiver of the user k. Introducing the unit eigenvector x_k corresponding to the largest eigenvalue λ_k of C_k, the solution of (4) and, hence, the failure level are given by

$$\hat{w}_k = \sqrt{\frac{N_k SNIR}{\lambda_k}} \ x_k, \ \triangle P_{max} = r_{max} \frac{N_k SNIR}{\lambda_k}. \tag{5}$$

3. THE SPATIAL SEPARABILITY CHECK

Applying the spatial separability check to a channel l yields a positive number $c^{(l)}$ evaluating how well a set of K users can be separated by beamforming on the downlink. Since we assume that an SDMA base station can only handle a maximum number K_c of users in the same FTCDMA channel, $K^{(l)} = K_c$ automatically results in $c^{(l)} = +\infty$ (i.e. no separability).

For clarity reasons, we will from now on do without the superscript $(.)^{(l)}$. The number $1 + K^{(l)}$ of users in any channel l will be replaced by K. The already allocated users will be indexed with $1 \cdots K-1$ and the new one with K. The spatial covariance matrices $C_1 \cdots C_K$ are assumed to be a-priori known. The optimal weight vectors before and after the allocation of the new user will be denoted by $\tilde{w}_1 \cdots \tilde{w}_{K-1}$ and $\hat{w}_1 \cdots \hat{w}_K$.

3.1 The optimal criterion

As indicated in the previous chapter, the optimal criterion c_1 is the power increase $\triangle P$ as defined in (3). To get the optimal weight matrix $\hat{W}$ the full beamforming procedure has to be executed. The corresponding mathematical problem to be solved is the minimization of the quadratic cost function

$$\overset{min}{w_1 \ldots w_K} \{\|W\|_F^2 = \sum_{k=1}^{K} w_k^H w_k\} \tag{6}$$

with the K nonlinear constraints

$$\frac{S_{y,y}}{SNIR} = N_y + \sum_{\substack{z=1 \\ z \neq y}}^{K} S_{y,z} \ , \ y = 1 \ldots K. \tag{7}$$

Executing L minimizations of that kind would result in a prohibitively high computational load. Even "linearized" approximations like those presented in [7] and [8] need at least $L + \sum_{l=1}^{L} K^{(l)}$ generalized eigendecompositions of Hermitian $M \times M$ matrix pairs. Therefore, suboptimal criteria will be presented in the next two sections.

3.2 A subspace-oriented approximation

If the subspaces spanned by the matrixes C_1 and C_2 of two users are orthogonal to each other, maximizing the power $S_{1,1} = w_1^H C_1 w_1$ for user 1 does not result in any interference $S_{2,1} = w_1^H C_2 w_1$ for user 2 and vice versa. This leads us to the following heuristic: the spatial separability of a set of users is determined by the minimum distance $dist(C_i, C_j)$ of the subspaces spanned by the covariance matrix pairs C_i and C_j $(i < j \bigwedge i, j = 1 \cdots K)$.

According to the definition in [9] the subspace distance is always in the range $[0; 1]$. The orthogonal projection P of a Hermitian matrix C can be calculated from the matrix U yielded by the singular value decomposition (SVD) $C = U \Sigma U^H$. Note that only one SVD per allocation is necessary provided all matrices U_i corresponding to the previously allocated users were saved.

Unfortunately, $dist(C_i, C_j)$ always yields 0, if C_i, C_j or both have full rank. Considering that in diffuse multipath environments all covariance matrices tend to have full rank, their subspaces need to be truncated to yield a feasible result.

Our investigations showed that in terms of channel allocation fixing the rank of C to $M - 1$ is the most effective way to truncate the subspace of the spatial covariance matrices. Therefore, our criterion c_2 will be defined as follows:

$$c_2 = \min_{i,j} \{ \| \bar{\boldsymbol{U}}_i \bar{\boldsymbol{U}}_i^H - \bar{\boldsymbol{U}}_j \bar{\boldsymbol{U}}_j^H \|_2 \} \ , \ i < j \bigwedge i,j = 1 \cdots K, \tag{8}$$

with $\bar{(.)}$ indicating the deletion of the rightmost column. If the subspaces of any two users are identical, c_2 yields 0 (no separability), if they are all orthogonal to each other, c_2 yields 1 (optimal separability).

3.3 Interference-oriented approximations

Alternatives to the mentioned algebraic approach are those directly evaluating the interference produced by the weight vectors.

First, we will define the forward noise-and-interference F (inflicted on the new user):

$$F = N_K + \sum_{z=1}^{K-1} S_{K,z}. \tag{9}$$

In order to compensate for F a provisional weight vector $\breve{\boldsymbol{w}}_K$ can be computed in a way similar to (5):

$$\breve{\boldsymbol{w}}_K = \sqrt{\frac{F \cdot SNIR}{\lambda_K}}\ \boldsymbol{x}_K. \tag{10}$$

Note that $\boldsymbol{x}_K$ has to be computed only once for each new user and that it can be reused for the calculation of the optimal weight matrix $\hat{\boldsymbol{W}}$ [7] [8].

Setting out from $\breve{\boldsymbol{w}}_K$, the backward interference B (inflicted by $\breve{\boldsymbol{w}}_K$) and the total noise-and-interference T can be calculated as follows:

$$B = \sum_{y=1}^{K-1} S_{y,K} \ , \ T = \sum_{y=1}^{K} \left(N_y + \sum_{\substack{z=1 \\ z \neq y}}^{K} S_{y,z} \right). \tag{11}$$

Setting out from F, B and T we will define the following three criteria:

$$c_3 = F \ , \ c_4 = B \ , \ c_5 = \frac{T}{\sum_{y=1}^{K-1} Sy,y}. \tag{12}$$

4. SIMULATIONS

A total of 26 criteria were compared to the optimal criterion c_1 in terms of performance. The criteria were based on the subspace distance and the three types of interference F, B and T. In order not to impair the clarity of the results only the best representative of each of the mentioned four categories (namely the criteria $c_2 \cdots c_5$) can be seen in the figures 2 to 4. Each criterion was tested by means of 600 simulation runs described below.

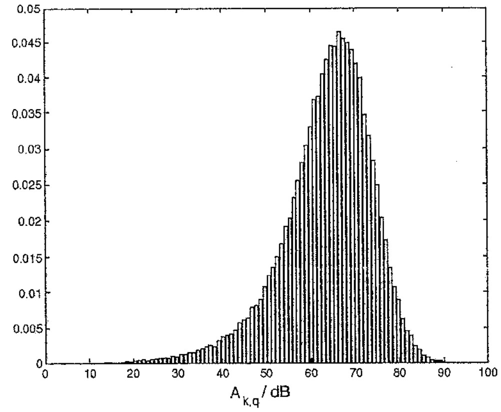

Figure 1: Probability density of the path attenuation factor $A_{k,q}$

Setting out from $L = 16$ channels, each occupied by a single user, another 24 users are successively requesting for a communication channel. Each new user undergoes the allocation procedure with a separability test based on one specific criterion and will be either rejected or allocated to one of the channels $1 \cdots 16$. The maximum number of users per channel was $K_c = 4$.

We are assuming a ring-shaped SDMA cell which has a base station in its center equipped with a uniform linear 8-element antenna array. The maximum distance from any user to the base station is given by the outer ring radius $r^{(o)} = 5$ km; the minimum distance by the inner ring radius $r^{(i)} = 0.1$ km. The user locations are equally distributed in the ring and independent from each other. Assuming there is a densely built-up area, the average attenuation corresponding to the user distance r_k can be approximated by $\bar{A}_k = 40 lg(r_k / r^{(i)})$dB.

The numbers Q_k of propagation paths are assumed to be equally distributed in $[1; 3]$. The path attenuation factors $A_{k,q}$ are log-normally distributed with the Suzuki parameter $S = 6$dB and the average $\bar{A}_k$. The probability density $p(A_{k,q})$ is depicted in fig. 1.

The mean azimuths $\bar{\psi}_{k,q}$ of the propagation paths are equally distributed in the range $[-180^0; +180^0]$, whereas the mean elevations are constant ($\bar{\theta}_{k,q} = 0^0$). The numbers $R_{k,q}$ of subpaths per path are equally distributed in the range $[1; 50]$. The azimuths $\psi_{k,q,r}$ and elevations $\theta_{k,q,r}$ of all subpaths are both Gauss-distributed with the means $\bar{\psi}_{k,q}$ and $\bar{\theta}_{k,q}$ and standard deviations $\delta\psi_{k,q} = \delta\theta_{k,q} = 3^0$.

Fig. 2 shows the average number of users per FTDMA channel after all 24 users have requested a communication channel. The average number of failures before a new user will be either allocated or rejected is depicted in fig. 3. Fig. 4 shows the average amount of electromagnetic power the base station antenna array has to emit per user to maintain the SNIRs.

5. CONCLUSIONS

According to our simulation results the subspace-based approaches are by far outperformed by the interference-oriented approximations. The best approximation is given by the criterion c_5 which is a normalized variation of the total noise-and-interference T. Its performance with respect to the channel allocation problem does in general not lag far behind c_1 even though its computational costs are lower by a factor between 10^2 and 10^4.

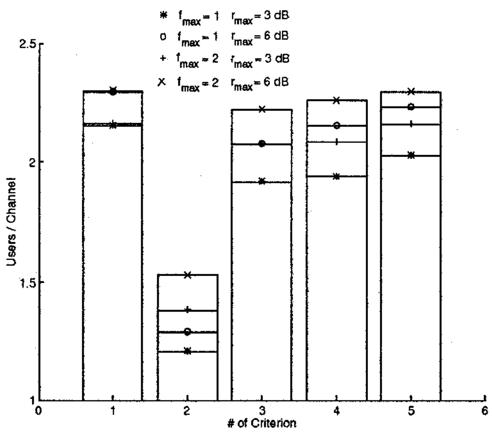

Figure 2: Users per FTCDMA channel after 24 requests

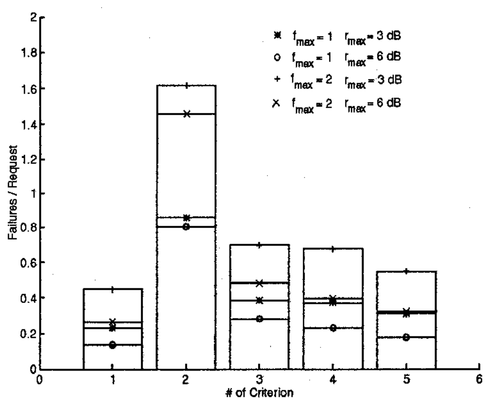

Figure 3: Failures per request

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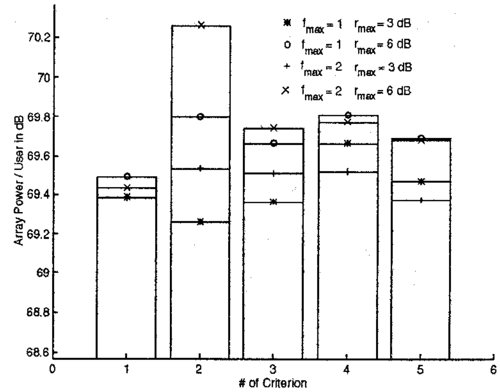

Figure 4: Array power per user after 24 requests

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