DOWNLINK PERFORMANCE OF ADAPTIVE ANTENNAS WITH NULL BROADENING

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Abstract – We compare different null broadening schemes and their ability to decrease the radiated interference for the co-channel users in a Space Division Multiple Access system with adaptive antennas. By link level simulations of the GSM1800 system in urban and suburban environments we show that a gain of up to 8dB in SNIR is feasible with null broadening. Therefore adequate null broadening seems to be a must in the downlink beamforming process.

I. INTRODUCTION

Adaptive Antennas at the base station are one possibility to satisfy the increasing demand for cellular mobile communications. With SDMA (Space Division Multiple Access) we can serve more than one user on a single traffic channel (same frequency and timeslot) of a TDMA system [1].

Several algorithms have been proposed for the uplink to detect the signals from different users at the base. But the goal is to find methods to achieve the same capacity increase in the downlink also. In TDMA systems like GSM and its derivates, interference suppression at the MS is not possible with the standard terminals. Therefore the received SNIR (Signal-to-Noise-and-Interference Ratio) at the mobile is a direct measure for the link quality. As a consequence, appropriate beamforming by the adaptive antenna at the base station is necessary to provide a satisfactory link quality for all co-channel users within one traffic channel.

In FDD (Frequency Division Duplex) systems fading is uncorrelated in uplink and downlink and the frequency dependent array response is different. This makes downlink beamforming a very challenging task [2] because the antenna weights determined for uplink reception should not be used also for the downlink transmission [3]. One practical method is to utilize the from the received uplink data estimated the directions-of-arrival (DOA) to calculate the complex antenna weights for the downlink [4]. But in urban environments angular spreads (AS) of up to $15°$ have been measured [5]. If we only use the estimated DOAs for the downlink beamforming process we produce a high interference level because the nulls pointed towards the co-channel users are too narrow.

In this study, we compare three different null broadening methods [6] [7] [8] and their ability to keep the produced co-channel interference as low as possible. Thereby we estimate the DOAs with Unitary ESPRIT [9] and the corresponding power values using a simple beamformer. With this information and the null broadening schemes we create the spatial covariance matrix for the downlink frequency and calculate the antenna weights with the "Optimum Combining Beamformer" [10]. These complex weights are then used for downlink transmission.

The paper is organized as follows. The signal model is presented in Section II. The three considered null broadening techniques are described in Section III. The simulation environment and the results are derived in Section IV and Section V. Finally, concluding remarks are given in Section VI.

II. DATA MODEL

We assume that K co-channel users are served on the same frequency and timeslot by a base station with an adaptive antenna array. Assuming a narrowband signal model, the baseband signal received at time t at the M-element antenna array with L_k paths for the k-th user is:

$$\boldsymbol{x}(t) = \sum_{k=1}^{K} \sum_{l=1}^{L_k} A_{kl} \boldsymbol{a}(\theta_{kl}, f_u) s_k(t - \tau_{kl}) + \boldsymbol{n}(t) \quad (1)$$

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with

$$\boldsymbol{a}(\theta, f_u) = \left[1, e^{-j2\pi d \frac{f_u}{c}\sin\theta}, \dots, e^{-j2\pi d \frac{f_u}{c}(M-1)\sin\theta}\right]^T \tag{2}$$

where A_{kl} denotes the amplitude of the l-th path of the k-th user and τ_{kl} its corresponding delay, respectively. Further, $s_k(t)$ is the complex valued signal transmitted by the k-th user and $\boldsymbol{n}(t)$ indicates the M-dimensional complex white Gaussian noise vector. In (2) $\boldsymbol{a}(\theta, f_u)$ represents the array steering vector of a wave impinging from an azimuthal direction θ at an M-element uniform linear array (ULA) with an inter-element spacing d at the uplink frequency f_u. From the received signal we estimate $\hat{L}_k$ dominant DOAs $\hat{\theta}_{kl}$ and the corresponding power values $\hat{P}(\hat{\theta}_{kl})$ for each user. Equipped with these estimates we calculate the spatial covariance matrix of the k-th user at the downlink frequency

$$\boldsymbol{R}_k = \sum_{l=1}^{\hat{L}_k} \hat{P}(\hat{\theta}_{kl})\boldsymbol{a}(\hat{\theta}_{kl}, f_d)\boldsymbol{a}^H(\hat{\theta}_{kl}, f_d). \tag{3}$$

In the same way we define the interference covariance matrix $\boldsymbol{Q}_i$ as

$$\boldsymbol{Q}_i = \sum_{k \neq i} \boldsymbol{R}_k + \sigma_N^2 \boldsymbol{I}, \tag{4}$$

where σ_N^2 and $\boldsymbol{I}$ denote the noise variance and the $M \times M$ identity matrix, respectively. We compute the complex antenna weights for the i-th user as the dominant generalized eigenvalue of $[\boldsymbol{R}_i, \boldsymbol{Q}_i]$. This well known beamforming concept corresponds to maximizing the SNIR in the uplink [10] and the estimated ratio of signal to co-channel interference power for the i-th user in the downlink

$$\boldsymbol{w}_i = \arg\max_{\boldsymbol{w}_i} \frac{\boldsymbol{w}_i^H \boldsymbol{R}_i \boldsymbol{w}_i}{\boldsymbol{w}_i^H \boldsymbol{Q}_i \boldsymbol{w}_i}. \tag{5}$$

The Gaussian white noise term in (4) provides the necessary antenna gain of the adaptive array in the downlink. We use the complex weights calculated this way for downlink transmission.

III. NULL BROADENING

For steering broad nulls towards the co-channel users we modify the interference covariance matrices of the K users. Different ways to include the angular spread into the interference covariance matrix estimate are discussed in this section.

Higher-Order Null Broadening

The principle of this method is presented in [6]. To obtain a null into a certain direction θ, the corresponding weight vector $\boldsymbol{w}$ has to fulfill

$$\boldsymbol{w}^H \boldsymbol{a}(\theta, f_d) = 0. \tag{6}$$

We point a higher order null to the dedicated directions to broaden the null width, i.e. by forcing the order derivative constraints

$$\frac{\partial^n(\boldsymbol{w}^H \boldsymbol{a}(\theta, f_d))}{\partial \xi^n} = 0, \qquad \forall n = 0, \dots, N \tag{7}$$

where N denotes the order of the null and $\xi = (2\pi d/\lambda_d)\sin\theta$. Taking the structure of the array steering vector (2) into account, we rewrite the desired properties

$$\begin{aligned} \boldsymbol{w}^H \boldsymbol{B}^n \boldsymbol{a}(\theta, f_d) &= 0 \qquad \forall n = 0, \dots, N \\ \boldsymbol{B} &= \mathrm{diag}\{0, d/\lambda_d, \dots, (M-1)d/\lambda_d\}. \end{aligned} \tag{8}$$

We finally introduce the modified interference covariance matrices

$$\widetilde{\boldsymbol{Q}}_i = \boldsymbol{Q}_i + \boldsymbol{B}\boldsymbol{Q}_i\boldsymbol{B} + \dots + \boldsymbol{B}^N \boldsymbol{Q}_i \boldsymbol{B}^N. \tag{9}$$

In this approach we can only choose the order of the null pointed towards the co-channel interferers. Therefore the broadness of the nulls is adjusted in a certain step size and it is not possible to adapt it smoothly to the actual propagation conditions (especially the angular spread).

Angular Spread based Approach

The *Angular Spread based Approach* [7] includes the angular spread corresponding to the estimated DOA into the spatial covariance matrix. An improved estimate of the spatial covariance matrix of the k-th user compared to (3) is given by

$$\boldsymbol{R}_k = \sum_{l=1}^{\hat{L}_k} \hat{P}(\hat{\theta}_{kl})\boldsymbol{a}(\hat{\theta}_{kl}, f_d)\boldsymbol{a}^H(\hat{\theta}_{kl}, f_d) \odot \boldsymbol{S}(\hat{\theta}_{kl}, \hat{\sigma}_{kl}) \tag{10}$$

with

$$[\boldsymbol{S}(\hat{\theta}_{kl}, \hat{\sigma}_{kl})]_{pq} = e^{-2[\pi \frac{d}{\lambda_d}(p-q)]^2 \hat{\sigma}_{kl}^2 \cos(\hat{\theta}_{kl})}, \tag{11}$$

where $\odot$ and $[\cdot]_{pq}$ denote the Schur-Hadamard element-by-element matrix product and the pq-th element of a matrix, respectively. The parameter $\hat{\sigma}_{kl}$ represents the estimated angular spread of the corresponding DOA $\hat{\theta}_{kl}$. We use the worst case spreading matrix

$$[\boldsymbol{S}_{max}]_{pq} = e^{-2[\pi \frac{d}{\lambda_d}(p-q)]^2 \sigma_{max}^2} \tag{12}$$

and define

$$\widetilde{\boldsymbol{Q}}_k = \boldsymbol{Q}_k \odot \boldsymbol{S}_{max} \tag{13}$$

to apply this null broadening method directly on the interference covariance matrix of (4). Instead of the specific values as in (10) we include the upper bound of the estimated angular spread σ_{max} in the interference covariance matrix. This worst case approximation has the effect of overestimating the angular perturbation for sources near end-fire, but the influence on the SNIR distribution is negligible [12]. With this method we can adjust the broadness of the nulls smoothly.

Multiple Nulling

In this approach we include a few closely spaced directions in the estimate of the interference covariance matrix $\boldsymbol{Q}_i$. By including some additional signal components which are equidistantly placed over the desired nulling sector we simulate the angular spread. We compute the modified estimate of the interference covariance matrix of (4)

$$\widetilde{\boldsymbol{Q}}_i = \sum_{k \neq i} \sum_{l=1}^{\hat{L}_k} \hat{P}(\hat{\theta}_{kl}) \boldsymbol{U}_{kl} + \sigma_N^2 \boldsymbol{I}, \qquad (14)$$

with

$$\boldsymbol{U}_{kl} = \sum_{\zeta=-\Upsilon_{kl}}^{+\Upsilon_{kl}} \boldsymbol{a}(\hat{\theta}_{kl} + \zeta \Delta_{kl}) \boldsymbol{a}(\hat{\theta}_{kl} + \zeta \Delta_{kl})^H, \qquad (15)$$

where $(2\Upsilon_{kl} + 1)$ and Δ_{kl} represent the numbers of the minor separated directions and the spacing of these directions of the l-th DOA of the k-th user, respectively. The beamforming algorithm puts nulls in these directions and as a consequence the null width is broadened [8]. Nevertheless the application of this method is restricted to DOA based covariance matrix estimation while the two other methods can be used with every estimate of the spatial covariance matrix.

IV. SIMULATION ENVIRONMENT

The simulation environment models a GSM 1800 system applying an adaptive antenna for SDMA. We serve K=2 users simultaneously on a single traffic channel in a 120° sector cell. We used a uniform linear array (ULA) with M=8 antennas and an inter-element spacing of d=$\lambda_d/2$.

We carried out the simulations using the Geometry-Based Stochastic Channel Model (GSCM) [11]. In our case, the scattering model consists of one scattering disk with 20 scatterers, which represents the local scattering (reflections) near the mobile's position. The principle of the GSCM is illustrated in Fig. 1. The scatterer-MS distance in the scattering circle is taken from a one-sided Gaussian distribution with a standard deviation defined by the radius of the scattering disk R_{disk}. The scatterers are stationary and the mobile moves through the scatterering scenario. A user separation of at least 35° guaranteed the necessary angular separation for SDMA [13].

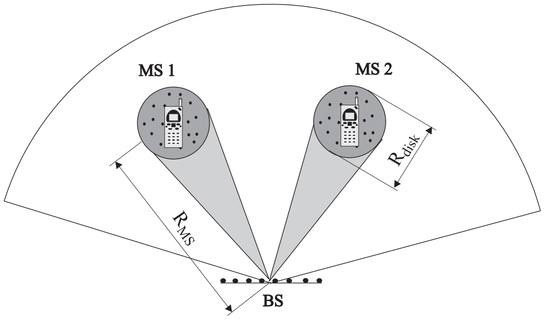

Figure 1: Principle of the Geometry-based Stochastic Channel Model.

In the downlink the received signal at the position of the i-th mobile $x_i(t)$ is given by

$$x_i(t) = \sum_{k=1}^{K} x_{i,k}(t) + n_i(t), \qquad (16)$$

$$x_{i,k}(t) = \sum_{l=1}^{L_i} A_{il} \boldsymbol{a}^H(\theta_{il}) \boldsymbol{w}_k s_k(t - \tau_{il}), \qquad (17)$$

where $x_{i,k}(t)$ denotes the signal transmitted for the k-th mobile received by the i-th MS. We take the received SNIR as the link quality measure. From (16) we get the definition of the SNIR at the i-th mobile

$$SNIR_i = \frac{\boldsymbol{x}_{i,i} \boldsymbol{x}_{i,i}^H}{(\boldsymbol{x}_i - \boldsymbol{x}_{i,i})(\boldsymbol{x}_i - \boldsymbol{x}_{i,i})^H}, \qquad (18)$$

where $\boldsymbol{x}_{i,k}$ is the sampled discrete time version of $\boldsymbol{x}_{i,k}(t)$. The noise level in our simulations was set to SNR=30dB.

V. SIMULATIONS

We performed simulations of 10000 GSM bursts and calculated the resulting SNIR distribution with different null broadening schemes in different environments. The angular spread of the signals can be estimated if there is only one scattering area (nominal DOA) per user [14]. But recent channel measurements have shown that the signals can also impinge from totally different directions at the array [15]. This problem has to be solved in the future to be able to exploit the gains of null broadening in suburban and urban environments.

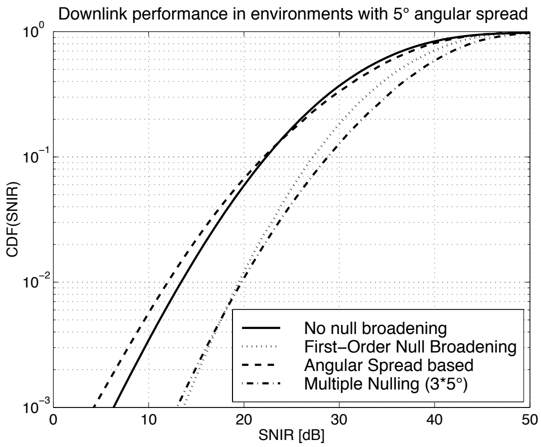

Figure 2: Cumulative distribution function of the received downlink SNIR in suburban environments with 5° angular spread.

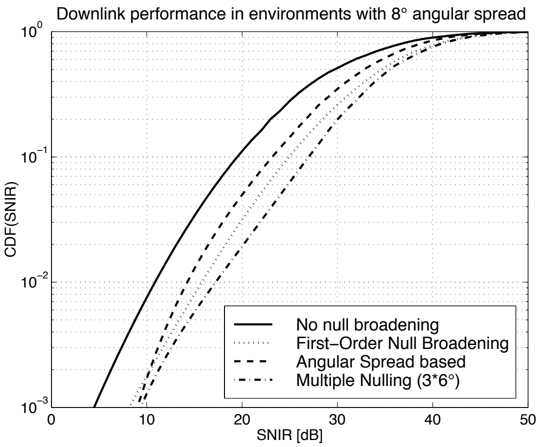

Figure 3: Cumulative distribution function of the received downlink SNIR in suburban environments with 8° angular spread.

We defined the angular spread by fitting the radius of the scattering disk corresponding to the geometrical relation $R_{disk} = R_{MS} \cdot \tan \frac{\sigma}{2}$ shown in Fig. 1, where σ denotes the angular spread. This angular spread value was used for the *Angular Spread based Approach.* For the two other null broadening scheme we selected those parameters which showed the best performance.

As an example for suburban propagation we took an angular spread of σ=5° and σ=8°. Even with small spreading of the users' signals in the angular domain (Fig.2) null broadening increases the SNIR by up to 6dB at the 1% level of the cumulative distribution function. But under such conditions the *Angular Spread based Approach* did not lead to a link quality improvement. For an angular spread of 8° (Fig.3) a gain of about 7dB is feasible.

An angular spread of σ=10° (Fig.4) and σ=12° (Fig. 5) was used to model typical urban propagation. In this environment a second-order null in the direction of the co-channel user (N=2 in (8)) showed better results than first order (not illustrated). Even in such bad propagation environments we exceed the SNIR threshold of 9dB for GSM at the 1% level. As a consequence SDMA with two users per traffic channel is also possible in urban areas when we apply null broadening.

In all scenarios the *Angular Spread based Approach* showed the worst performance. One cause therefore is that the geometrical definition of the angular spread used in this work sometimes overestimates the angular spread. The other two methods lead to comparable results. The *Higher-Order Null Broadening* performed very well, even though the possibility to adjust the broadness of the nulls smoothly is not given. In contrast to that the *Multiple Nulling* method can be easily adjusted, but the application is restricted to DOA based downlink beamforming.

VI. CONCLUSIONS

We showed that null broadening in the downlink of an SDMA/FDD system gives a gain of up to 8dB in SNIR. To balance up- and downlink given the lower downlink performance, the application of null broadening is mandatory in propagation environments with large angular spread.

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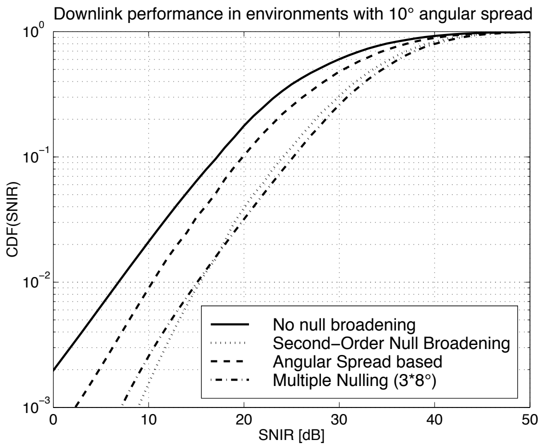

Figure 4: Cumulative distribution function of the received downlink SNIR in urban environments with 10° angular spread.

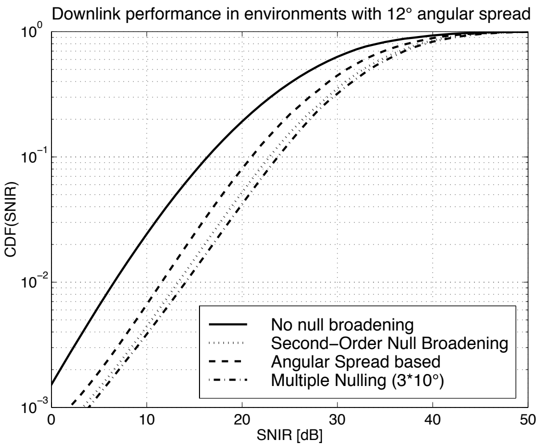

Figure 5: Cumulative distribution function of the received downlink SNIR in urban environments with 12° angular spread.

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