Performance of Downlink Nulling for Combined Packet/Circuit Switched Systems

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Abstract

In the evolution of 2nd generation mobile communication systems packet switched data transmission (e.g. GPRS/EGPRS in GSM Phase 2+) and circuit switched speech communication will be demanded in parallel. Directing nulls of the antenna pattern to active mobiles in the downlink beamforming process using antenna arrays at the base station may be useless in the case of packet data transmission. We show that even in combined packet/circuit switched mobile communication systems „gentle“ downlink interferer nulling dependent on propagation conditions and traffic distribution leads to performance and capacity improvements.

1. Introduction

The evolution of second generation mobile communication systems to wireless networks supporting packet data transmission (e.g. GPRS [1] of GSM) brings up additional challenges for the operation of adaptive antennas at the base station (BS).

During uplink reception, we directly react to the current user and interference situation. It is possible to point the main beam into the direction of the desired user and to suppress interference by steering nulls towards the interferers [2]. For downlink transmission the situation is totally different: the users served on the same timeslot and frequency in neighboring cells may change from uplink to downlink in packet switched data transmission. Thus, null steering for these interferers is impossible because the serving BS is unaware of the dynamic packet channel allocation in the distant cells using the same frequency. As a consequence, no interference rejection improvement due to null steering is possible compared to simple beampointing. Moreover, the beampointing gain for the desired user will be slightly reduced. Some degrees of freedom in the beamforming process are wasted to direct the nulls towards non-active "supposed" interfered users. They otherwise could have been used to increase the beamforming gain for the desired user.

This situation worsens with increasing angular spread (AS) of the mobile radio channel caused by rich multi-path propagation. In such propagation conditions broad nulls become necessary to fully exploit the interference rejection capabilities of the adaptive antenna array [3]. But these broad nulls also reduce the beamforming gain significantly.

In upcoming systems, however, the traffic profile will be a mixture of circuit and packet switched wireless connections, which will be location and service dependent. We show by simulation that in such a system "gentle" null steering will still lead to a performance benefit over standard beampointing without any kind of downlink interferer nulling.

2. Data Model and Uplink Beamforming

We assume that the serving base station receives the signals of K mobiles in the uplink. The received signal from the k-th user, assuming a narrowband signal model, at time t at the M-element antenna array with L_k signal paths is

$$\boldsymbol{x}_k(t) = \sum_{l=1}^{L_k} A_{k,l} \cdot \boldsymbol{a}(\theta_{k,l}) \cdot s_k(t - \tau_{k,l}), \qquad (1)$$

where $A_{k,l}$ denotes the amplitude of the l-th path of the k-th user and $\tau_{k,l}$ its corresponding delay, respectively. Further, $s_k(t)$ is the complex valued signal transmitted by the k-th user in the uplink and $\boldsymbol{a}(\theta_{k,l})$ the array steering vector of the array for the l-th multi-path component. The total received signal can be represented as the superposition of the signals of the served user (k=1), the interferers in the neighboring cells as well as thermal noise

$$\boldsymbol{x}(t) = \boldsymbol{x}_1(t) + \sum_{k=2}^{K} \boldsymbol{x}_k(t) + \boldsymbol{n}(t), \qquad (2)$$

where $\boldsymbol{n}(t)$ indicates the M-dimensional complex valued white Gaussian noise vector.

The received Signal-to-Noise-plus-Interference-Ratio (SNIR) after beamforming in the uplink using the complex antenna weights $\boldsymbol{w}$ can be written as

$$SNIR_{rec} = \frac{\boldsymbol{w}^H \cdot \boldsymbol{R} \cdot \boldsymbol{w}}{\boldsymbol{w}^H \cdot \boldsymbol{Q} \cdot \boldsymbol{w}}. \tag{3}$$

In (3), $\boldsymbol{R}$ and $\boldsymbol{Q}$ represent the spatial covariance matrices of the desired user and of interference plus noise, respectively,

$$\boldsymbol{R} = E\left\{\boldsymbol{x}_1(t) \cdot \boldsymbol{x}_1^H(t)\right\},$$
$$\boldsymbol{Q} = \sum_{k=2}^{K} E\left\{\boldsymbol{x}_k(t) \cdot \boldsymbol{x}_k^H(t)\right\} + E\left\{\boldsymbol{n}(t) \cdot \boldsymbol{n}^H(t)\right\}. \tag{4}$$

The complex valued antenna weights maximizing the received SNIR [4] are given by

$$\boldsymbol{w} = \arg\max_{\boldsymbol{w}}\left\{SNIR\right\} = \arg\max_{\boldsymbol{w}}\left\{\frac{\boldsymbol{w}^H \cdot \boldsymbol{R} \cdot \boldsymbol{w}}{\boldsymbol{w}^H \cdot \boldsymbol{Q} \cdot \boldsymbol{w}}\right\}. \tag{5}$$

The solution of (5) is the dominating generalized eigenvector of the matrix pair [$\boldsymbol{R}$, $\boldsymbol{Q}$].

3. Downlink Beamforming

In the downlink the situation for our array processing unit is totally different. We do not know the positions of the interferers and have to assume that they do not change from uplink to downlink. Therefore we can only try to maximize the received power at the desired mobile station by pointing the main beam into the direction of the desired user and minimize the interference radiated to the users in the neighboring cells by directing nulls in their angular position. In analogy to the uplink, the received power at the k-th mobiles position is written as

$$P_k = \boldsymbol{w}^H \cdot \boldsymbol{R}_k \cdot \boldsymbol{w}, \tag{6}$$

where $\boldsymbol{R}_k$ denotes the spatial covariance matrix of the k-th user. For the desired user the received power is wanted signal power, for all other users (k=2...K) the received power acts as disturbing interference.

For simplicity, we do not distinguish between uplink and downlink covariance matrices in this paper. Of course the uplink and downlink covariance matrices are not identical due to the uncorrelated fading in up- and downlink and the frequency dependent antenna array response (only in systems with Frequency Division Duplex – FDD). But the spatial covariance matrices can be transformed from uplink to downlink using the spatial covariance matrix transformation ASCOFT [5].

We use (5) to calculate the complex antenna weights for the downlink beamforming process. The weight vector automatically places nulls into the direction of the users in neighboring cells and forms a main beam directed towards the desired user. Using this algorithm, the depth of the nulls can be controlled by adjusting the diagonal loading factor η [6] in the spatial covariance matrix $\boldsymbol{Q}$. The more spatially white components we include in $\boldsymbol{Q}$ by using

$$\boldsymbol{Q} = \sum_{k \neq 1} \boldsymbol{R}_k + \eta \cdot \frac{1}{M} sum\left(diag\left(\sum_{k \neq 1} \boldsymbol{R}_k\right)\right) \cdot \boldsymbol{I} \tag{7}$$

the weaker the nulling is made. This kind of "gentle" nulling, i.e. no deep nulls, is illustrated in Fig. 1. Obviously, the diagonal loading factor η determines the gain into the direction of the desired user (θ_{user}=-22°) and also the null depth in the direction of the interferers (θ_{Int1}=-55°, θ_{Int2}=25°, θ_{Int3}=56°). Setting η=1 results in equi-powered interference and spatially white diagonal loading contribution of $\boldsymbol{Q}$.

For an extremely high diagonal loading factor (η»1) the algorithm of (5) reduces to the ordinary beampointing algorithm,

$$\boldsymbol{w} = \arg\max_{\boldsymbol{w}}\left\{S\right\} = \arg\max_{\boldsymbol{w}}\left\{\boldsymbol{w}^H \cdot \boldsymbol{R} \cdot \boldsymbol{w}\right\}, \tag{8}$$

maximizing the received power S of the desired user. In this case the algorithm only directs the main beam into the direction of the desired user to maximize the downlink signal gain without any kind of downlink interferer nulling.

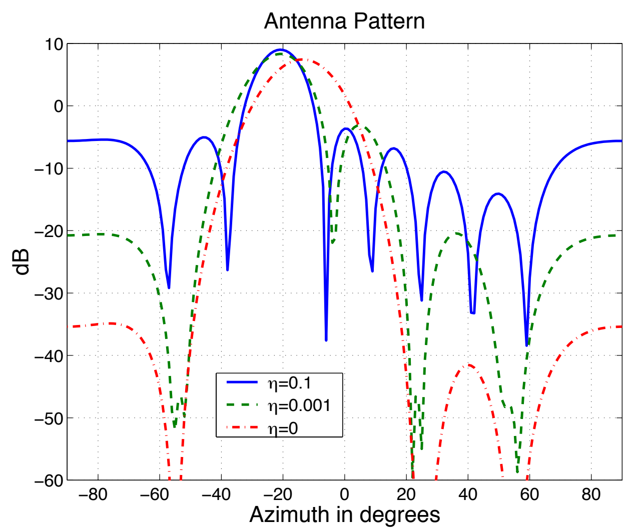

Figure 1: Antenna pattern with different diagonal loading factors and therefore varying null depth.

4. Circuit vs. Packet Switched

Circuit switched users occupy the same traffic channel for a relatively long time. In this case the nulls placed to decrease the produced interference are definitely reasonable. But users on a packet switched traffic channel may change from uplink to downlink. This effect is illustrated in Fig. 2.

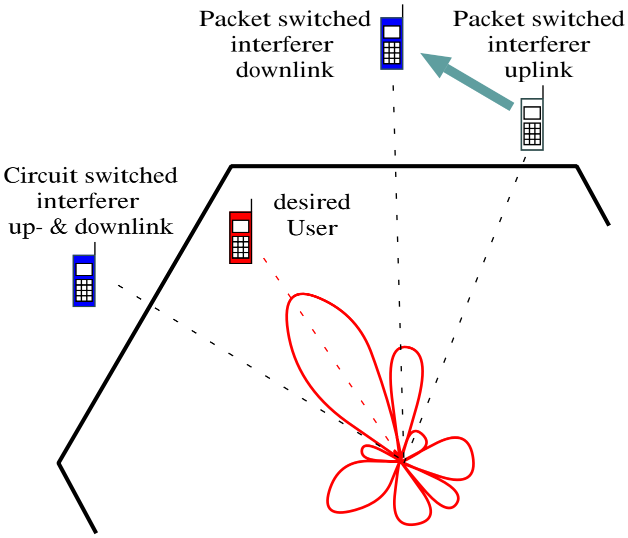

Figure 2: Change in the traffic channel allocation from uplink to downlink. The arrow denotes the change of packet switched traffic allocation from up- to downlink.

We can estimate the spatial channel for the desired user as well as for the active interferers from the received uplink data. Using this information for downlink beamforming, we can increase the received signal for the desired user and decrease the power received by the interferers. But this is only possible, if the interferers in uplink and downlink are the same. This will not be the case in packet switched transmission where dynamic channel allocation is performed. If the downlink beamforming algorithm acts according to the actual uplink traffic situation by directing nulls in the produced antenna pattern towards the users in the neighboring cells, it will use the spatial covariance matrices of these users in the weight calculation process. Circuit switched users will be active in the uplink as well as in the downlink ($\boldsymbol{R}_{circuit,up}=\boldsymbol{R}_{circuit,down}$). Packet switched users active in the uplink traffic channel might be inactive in the downlink. An other packet switched user will be active in the corresponding downlink traffic channel and thus the situation changes ($\boldsymbol{R}_{packet,up}\neq\boldsymbol{R}_{packet,down}$). Since no null can be placed in an unknown direction the produced downlink interference for these packet switched users is larger than originally intended by the weight calculation algorithm (compare Fig. 2). Additionally the degrees of freedom used to place the nulls for their corresponding uplink counterparts are wasted, and they decrease the beamforming gain for the served user within the cell.

We therefore have to perform the beamforming in the downlink for a combined circuit/packet switched mobile communication system in favor of the downlink signal gain. This is done by "gentle" downlink nulling, where we do not fully use the potential downlink interference suppression capabilities of the antenna array. Using this strategy, the nulling gain for circuit switched users is weakened but still profitable. The antenna gain for the desired user and also interference rejection for packet switched users is similar compared to simple beampointing.

5. Simulation Environment

We simulate a 2.5th generation mobile communication system. There will be, concurrently, circuit switched transmission (e.g. speech) and packet switched transmission (e.g. data). This means that the traffic situation (relation between circuit and packet switched data) will strongly depend on the specific location of the base station. We concentrate on the link level performance evaluation of adaptive antennas of a combined packet/circuit switched network. We consider a single isolated BS and evaluate the gain due to the adaptive antenna for the desired user as well as the interference suppression for the users not of interest. Our goal is not to show the capacity enhancement of the network (at system level) because of the big variety of traffic dependent system parameters. Thus our results are independent of system parameters such as the cluster size or specific propagation conditions as the path loss exponent.

In the simulations we use the Geometry based Stochastic Channel Model (GSCM) [7] to model the spatial behavior of the mobile radio channel. The base station is equipped with an 8-element uniform linear array with an inter-element distance of half the wavelength. We consider one desired user and three interferers, which are uniformly but randomly distributed in angle within the covered sector area of 120°. The signals of the users suffer rich multi-path propagation resulting in an angular spreading, which was varied in our simulations.

The desired user is assumed to have a circuit switched connection to its serving BS. The circuit switched interferers are active in both links. Packet switched interferers are assumed to be active only in up- or downlink. Therefore, when switching from uplink to downlink one interferer disappears and another pops up somewhere else randomly. Thus we generate a new packet switched interferer in the downlink with a different spatial channel impulse response (direction of arrival, etc.). In the uplink, the users are assumed to be spatial separable due to intelligent channel allocation [8]. This ensures the full interference suppression capabilities of adaptive antennas.

We assume to know the downlink spatial covariance matrices of users active in the uplink. As mentioned before [5], we calculate the complex valued antenna weights for downlink transmission using (5).

6. Simulation Results

Signal enhancement and interference rejection capabilities of the adaptive antenna are evaluated as space averaged mean values,

$$Gain = \frac{\left\| \boldsymbol{w}^H \cdot \boldsymbol{x} \right\|^2}{\sum_m \left\| x_m \right\|^2}, \quad (9)$$

where x_m denotes the signal of the m-th antenna element. Thus the given improvements are independent of the space selective fading.

The downlink signal gain for the desired user compared to a single antenna element depending on the null depth (diagonal loading factor) in case of an rms angular spread of 5° is illustrated in Fig. 3.

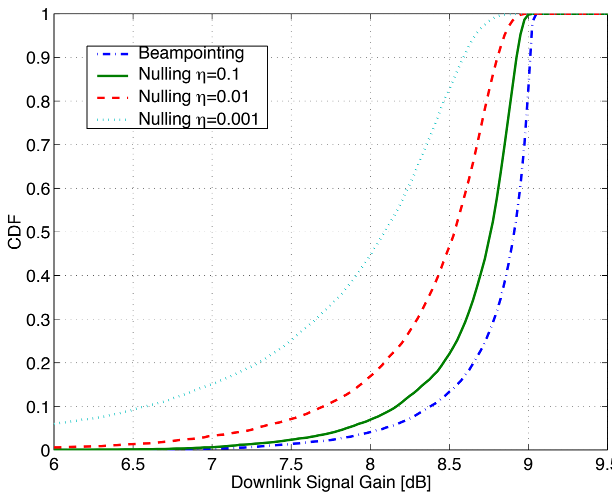

Figure 3: Downlink signal gain as a function of the diagonal loading factor (AS=5°).

The loss in the beamforming gain for "gentle" downlink interferer nulling (e.g. $\eta \approx 0.1$) compared to the simple beampointer of (8) is less than 0.2dB. However, we significantly decrease the produced interference due to downlink nulling. The case of 10% packet and 90% circuit switched users is shown in Fig. 4. There we get a reduction in the produced interference for circuit switched users in the neighboring cells by at least 8dB by directing the nulls in the downlink. The interference rejection with reference to a single antenna element I_{array}/I_{single} for packet switched users is identical for the adaptive transmission with and without nulling. However, the loss in the antenna gain for the desired user does not effect the results drawn in Fig. 4.

The higher the number of packet data users compared to circuit switched speech users, the smaller the performance improvement becomes.

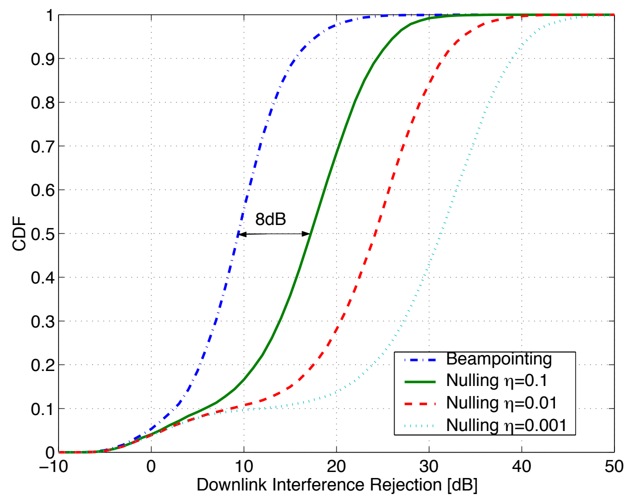

Figure 4: Downlink interference rejection - 10% packet and 90% circuit switched users (AS=5°).

In Fig. 5 we illustrate the relative interference rejection normalized to the standard beampointing algorithm

$$\frac{I_{Nulling} / C_{Nulling}}{I_{Beampointing} / C_{Beampointing}} \quad (10)$$

with a share of 75% packet and 25% circuit switched users in a multi-path environment with rms AS=5°. Also in this case we get a performance improvement in 58% of the cases (relative interference rejection >0dB). In 10% of the cases the gain for "gentle" downlink interferer nulling (η=0.1) is bigger than 8.5dB and only in 10% we loose more than 1.5dB.

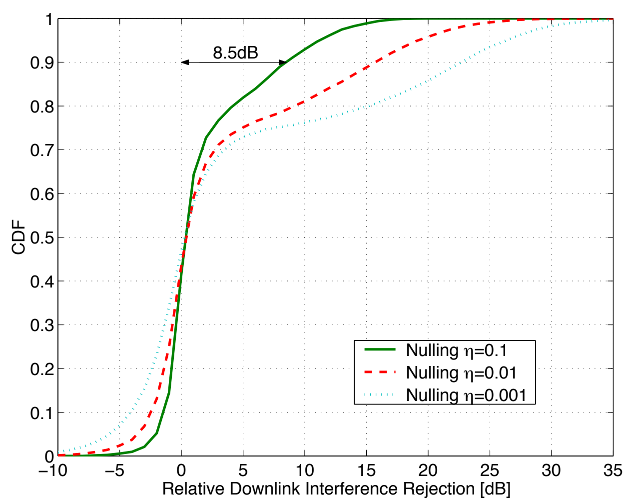

Figure 5: Relative downlink interference rejection - 75% packet switched and 25% circuit switched users (AS=5°).

But not only the traffic distribution defines the optimum diagonal loading factor for "gentle" downlink interferer nulling. The propagation conditions (especially the angular spread) also have a strong influence. The loss in the downlink signal gain with nulling compared to normal beampointing as a function of the angular spread and the diagonal loading factor η can be seen in Fig. 6. For a fixed diagonal loading factor the mean relative gain vanishes with increasing angular spread.

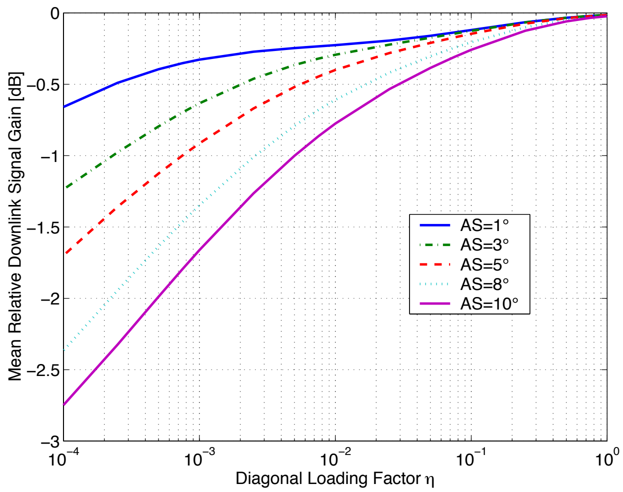

Figure 6: Mean relative downlink signal gain.

We have to consider the relative downlink interference rejection illustrated in Fig. 7 and not only the downlink signal gain. There exists an optimum diagonal loading factor dependent on the traffic distribution (fixed in this graph) and the physical propagation conditions (AS). With these diagonal loading factors a gain between 3 and 4.7dB depending on the angular spreading compared to simple beampointing is feasible.

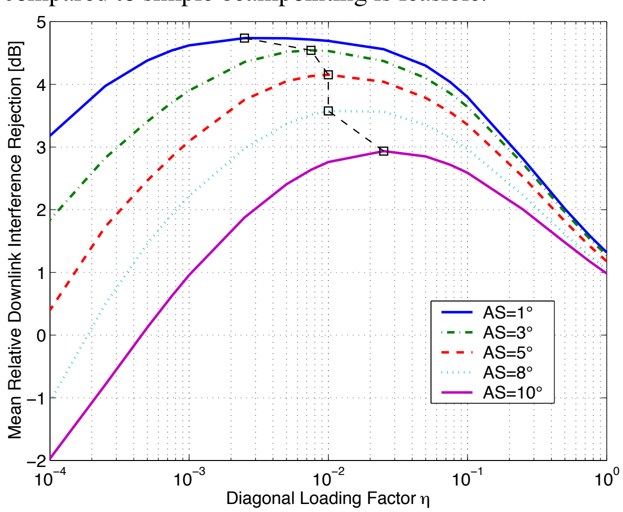

Figure 7: Mean relative downlink interference rejection - 75% packet switched and 25% circuit switched users.

Thus, even in inhomogeneous traffic situations and challenging propagation conditions the interference suppression with "gentle" downlink interference nulling improves the performance compared to simple beampointing. In real operating systems the diagonal loading factor η can be adjusted to the location and operator dependent traffic situations. In rural areas with a high share of circuit switched speech connections and small angular spreads, a more offensive nulling strategy ($\eta \ll 0.1$) is reasonable. But in areas with dominant packet switched traffic and strong multi-path propagation, "gentle" nulling ($\eta > 0.1$) will be more effective.

7. Conclusions

We showed by simulation that even in case of a combined packet/circuit switched wireless communication system using antenna arrays, adequate (gentle) downlink interference nulling outperforms standard beampointing methods.

The enhanced downlink interference suppression for the circuit switched users is still beneficial compared to the small loss in the downlink signal gain. The more packet switched users in the system and the richer the multi-path propagation (large angular spread) the more gentle the nulling has to be made to achieve the optimum performance using adaptive base station antennas.

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