REAL-TIME SMART ANTENNA PROCESSING FOR GSM1800 BASE STATION

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This paper is presented at the IEEE Vehicular Technology Conference '99 in Houston, Texas.

Abstract – We successfully implemented a smart antenna array processor for a GSM1800 base station. The entire array processing run–time is only 1ms, allowing real–time adaptation of the antenna pattern *every* GSM frame. The array processing is based on the estimation of the DOAs in the uplink. Separate DOA trackers for uplink and downlink, angular selection diversity, and beamforming with *broad* nulls guarantee robustness in mobile radio channels.
Measurements in a LOS scenario show that the DOA estimation accuracy is on the order of 1° for $0dB$ input SNR. BER measurements confirm the expected signal–to–noise gain of $\approx 9dB$ compared to the single antenna case. In case of one interferer a BER of 1% is reached for an input C/I of $-6.5dB$.

I. INTRODUCTION

Today smart antenna technology is in a mature state. Numerous concepts [1, 2] have been developed. Integrating those theoretical concepts in working solutions and judging their performance in mobile radio channels is today's challenge [3, 4].

We have developed the real–time Adaptive Antenna Array Processor **A^{3}P** that is embedded in a GSM1800 base station. The system works within the GSM standard and is compatible with frequency hopping. In a first stage the smart antenna is used to suppress co-channel interference, i.e. we apply Spatial Filtering for Interference Reduction (SFIR) [5].

We present results from measurements in a controlled LOS environment, as well as the performance of **A^{3}P** in a synthetic mobile radio channel.

II. GSM SMART ANTENNA BASE STATION

The demonstrator is based on a standard GSM1800 base station. For smart antenna processing eight transceivers are connected to an antenna array with half wavelength element spacing. All eight downconverted I- and Q-signals are sampled at symbol rate in a beamforming control unit (BFCU). The BFCU collects the samples for each GSM timeslot, and the data of one of the eight timeslots (TS) is transferred to the **A^{3}P**, which is implemented in a DEC Alpha 500MHz. The processing of the input data matrix $\mathbf{X}$ in only $1ms$ allows real–time adaptation of the beamforming weights *every* GSM frame (4.6ms). **A^{3}P** gains weight vectors for the uplink and downlink beamforming, carried out by the BFCU. The BFCU calculates, with the uplink weight vector $\mathbf{w}_{UL}$, the input signal $\mathbf{s} = \mathbf{w}_{UL}^H\mathbf{X}$ to the baseband detector. Similarly the downlink transmitter baseband signal is weighted with the downlink weight vector $\mathbf{w}_{DL}$ before transmission. To facilitate real–time reference measurements the BFCU includes simple smart antenna algorithms, like switched beam.

III. THE ADAPTIVE ANTENNA ARRAY PROCESSOR

A^{3}P's processing is based on direction of arrival (DOA) estimation. It is structured in four main sections:

- DOA estimation
  From the received input data in uplink the number of incoming wavefronts and their DOAs is estimated.

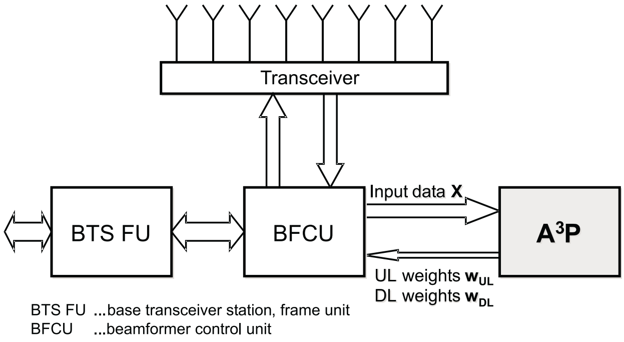

Figure 1: Smart antenna base station.

- DOA classification
  In a next step we identify those wavefronts that are originated from the user: First, we extract from the input data, with a spatial pre–filter, the spatially resolved wavefronts, each incident from an estimated DOA. Then, a user identification decides whether a wavefront (DOA) belongs to a user or to an interferer.
- Tracking
  The user DOAs are tracked to increase the reliability of the DOA estimates.
- Signal reconstruction — beamforming
  Finally a beamforming algorithm forms an antenna pattern with a main beam steered into the direction of the user, while minimizing the influence of the interfering wavefronts.

In downlink we need a weight vector that defines the excitation of the transmit antennas. The weight calculation differs from the uplink processing only in the fact that we employ separate tracking and subsequent beamforming algorithms. In the following we present the applied algorithms in more detail.

DOA estimation

Estimating the DOAs from array data is a well known problem in signal processing [6]. The input to the estimator is the calibrated baseband measurement matrix

$$\mathbf{X} = [\ \mathbf{x}_1 \quad \mathbf{x}_2 \quad \cdots \quad \mathbf{x}_N\ ],$$

where $\mathbf{x}_n$, $1 \leq n \leq N = 148$ is a column vector with $M = 8$ elements corresponding to the n–th temporal snapshot of the antenna array. We implemented three high–resolution algorithms, two subspace–based approaches and one spectral–based approach. The subspace–based algorithms are Unitary ESPRIT [7], and Unitary ESPRIT with *subspace tracking*.

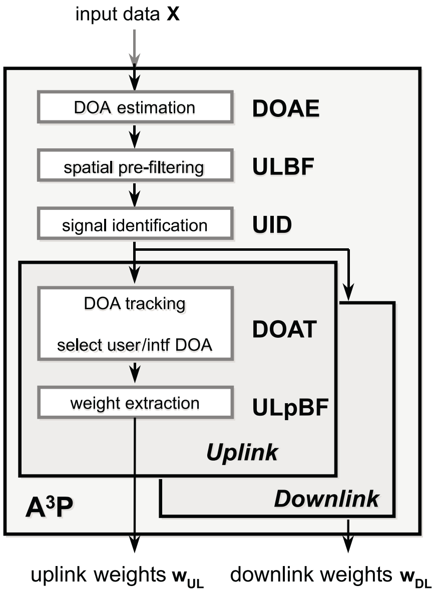

Figure 2: Adaptive Antenna Array Processor **A^{3}P**. **DOAE** … DOA estimation, **ULBF** … uplink beamformer, **UID** … user identification, **DOAT** … DOA tracking, **ULpBF** … uplink post beamformer, **DLBF** … downlink beamformer

Unitary ESPRIT. Unitary ESPRIT estimates the signal subspace by means of an Eigenvalue decomposition. From the estimated signal subspace the DOAs are calculated by solving the Invariance Equation and a subsequent spatial frequency estimation. The number of DOAs is estimated by an information theoretic criterion such as Rissanen's MDL [8].

Unitary ESPRIT with subspace tracking. Instead of *estimating* the signal subspace by means of an Eigenvalue decomposition, the subspace tracker PASTd (Projection Approximation Subspace Tracking with Deflation) [9] recursively *tracks* the signal subspace. To reduce the run–time we track the subspace only over a part of the GSM burst, i.e. $\mathbf{x}_{t_n}$, where $n = 1 \ldots 50$.

Minimum Variance Method. The third algorithm is a beamforming technique that calculates a spatial power spectrum by employing *Capon's Beamformer* [10], also known as Minimum Variance Method.

Finding the DOAs requires a 1D–search in the spectrum.

Other mobile radio applications of DOA estimators have failed because only one DOA was considered for the user. In a typical cellular mobile radio channel this is not sufficient. The **A^{3}P** considers *all* relevant paths that correspond to the user. Our system thus tries to identify all DOAs for the user and exploits this information to derive weight vectors for the final beamforming. The next two steps are required to categorize the DOAs found.

Spatial pre–filtering

The uplink beamformer **ULBF** extracts from $\mathbf{X}$ a spatially resolved wavefront for each of the L estimated DOAs. Thus we derive L weight vectors, $\mathbf{w}_l$, $1 \leq l \leq L$, whos' patterns steer beams into the wanted directions Θ_l, while nulling all other directions. As weight matrix, $\mathbf{W}_{ULBF} = [\mathbf{w}_{ULBF,1}\,\mathbf{w}_{ULBF,2}\cdots\mathbf{w}_{ULBF,L}]$, we apply the Moore–Penrose pseudo inverse [11] of the estimated steering matrix.

$$\hat{\mathbf{S}} = \mathbf{W}_{ULBF}^{H}\,\mathbf{X}_{\mathbf{midamble}}, \tag{1}$$

where

$$\hat{\mathbf{S}} = [\begin{array}{cccc} \hat{\mathbf{s}}_1^T & \hat{\mathbf{s}}_2^T & \cdots & \hat{\mathbf{s}}_L^T \end{array}]^T, \tag{2}$$

and $\mathbf{X}_{\mathbf{midamble}}$ is the part of the baseband measurement matrix $\mathbf{X}$ that contains the midamble (training sequence). The reconstructed signal vectors $\hat{\mathbf{s}}_l$, $1 \leq l \leq L$, contain the spatially resolved midambles corresponding to the l–th DOA.

User identification

In the second part of the DOA classification the user identification **UID** detects the spatially resolved midamble sequences to bit–level. By comparing the received midambles with the known user midamble, we calculate the number of bit errors within the training sequence. A spatially resolved wavefront, and thus the corresponding DOA, is attributed to a user, when the number of bit errors is smaller than a threshold. We so identify not only a single user path but *all* paths that correspond to the intended user. As a detector a standard sequence estimator was applied.

DOA tracker

A tracking algorithm (**DOAT**) is applied that is based on a bank of Kalman filters [12]. The tracker does not only prevent far–off estimates from disturbing the beamforming, but also prevents the DOA estimates from changing too much between two consecutive bursts. This is necessary since the mobile, in reality, does not move far during one GSM frame (4.6ms). Hence the variation in the DOA is negligible. Even if a path is obstructed and disappears, it takes several frames until a new path arises.

A^{3}P does not include tracking of the interferer DOAs, because the interferer situation will change from burst to burst with frequency hopping. For uplink and for downlink, separate trackers are used because the averaging in downlink requires larger memory length.

Signal reconstruction – beamforming

Finally we select the DOAs for signal reconstruction from the tracked user DOAs. We apply beamforming algorithms [13] in uplink and in downlink that place a main beam into the selected user DOA and *broad* nulls into the directions of the interferers. Note that the situation differs significantly to the pre–spatial filtering (**ULBF**). After **UID** we know whether a DOA belongs to a user or to an interferer. Also, the tracker has rendered the estimated DOAs more reliable.

Uplink post beamformer. For the uplink post beamformer **ULpBF** we select the user tracker (tracked DOA) with the strongest *instantaneous* power and thus implement *angular selection diversity.*

Downlink beamformer. Downlink fading is, of course, unknown at the base station. Thus we can only use averaged information derived from the uplink. For transmission the **DLBF** forms a beam into the direction with the largest *average* power. Also note that the uplink and downlink DOAs might differ in some situations, because at the uplink a path might be in a fading dip, but has still the largest mean power.

IV. DOA ESTIMATION ACCURACY

The DOA estimation is a key element in our smart antenna processing scheme. We define the DOA estimation accuracy as the standard deviation of the estimated DOA, when a *single plane* wave is incident.

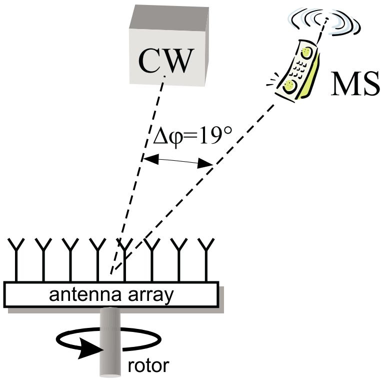

Figure 3: Measurement setup. The antenna array is mounted on a rotor. There are two signal sources with LOS to the BS present: a GSM mobile station (MS) and a continous wave (CW) signal generator.

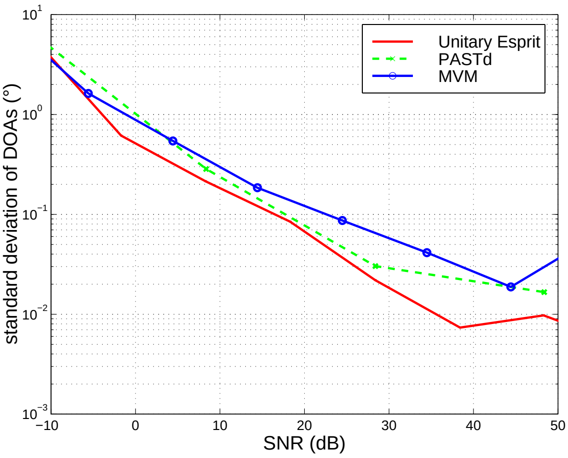

Figure 4: Measured estimation accuracy of the **DOAE** versus SNR when a single plane wave is incident from $\phi = 0°$.

We measured the estimation accuracy and compared it with computer simulations. For the measurements we used a continuous wave (CW) generator with line–of–sight to the BS (Fig. 3); there is no interfering signal source active. The BTS antenna array is mounted on a rotor to allow measurements for different DOAs. It is standing on the roof of a three–store high building that is surrounded by builings with similar — but not larger — height. We measured the estimated DOAs for different transmit powers of the CW generator.

The measured accuracy (Fig. 4) decreases linearly for all estimators. Because of non ideal system properties, like calibration errors and mutual coupling, the accuracy of the estimators does not decrease for large SNR. In case of the MVM the accuracy is additionally limited because of the finite spectral resolution of 0.01° (compare with simulated accuracy in Fig. 5). Most important is the similar behavior of all implemented algorithms: To get a DOA estimation accuracy of 1° all algorithms require an input SNR in the range of $0dB$[1].

To demonstrate the effect of DOA estimation errors on the BER we assess **A^{3}P** in a synthetic fading channel. We apply the Geometry–based Stochastic Channel Model (GSMC) [14]. The GSCM is based on local scatterers that are distributed around the MS, thus leading to small–scale fading. In our scenario the user was located at +10° and a single interferer at −20°. The angular spread of each path was about 1°. The mean input carrier–to–interference ratio (C/I) was $0dB$, the mean input SNR was set to $20dB$. We added to the ideal DOA a Gaussian distributed estimation error, i.e. we suppose an estimator with varying accuracy. We used two beamforming algorithms for the **ULpBF**: a beamformer with broad nulls and a conventional beamforming algorithm that places sharp nulls [13].

As long as the DOA estimation accuracy is smaller than 1° the BER performance of the beamformer with broad nulls is optimal (Fig. 6). In contrast a beamforming algorithm that places sharp nulls would require DOA estimates with higher accuracy.

In mobile radio channels the energy arrives from angular ranges [15] rather than from discrete DOAs. In such environments the DOA estimators sometimes fail, which results in poor — so called far–off — estimates. Steering a main beam into the wrong direction, in general, causes a burst BER of 50%, which in turn degrades the system performance considerably. Avoiding such situations is a key factor in DOA–based processing schemes [16]. **A^{3}P** minimizes the influence of far–off estimates by:

- classifying the waves incident from the estimated DOAs: the **UID** does in general *not* classify the spatially resolved signal of a far–off estimate as a user signal.
- selecting only significant interferers for beamforming: in case of a far–off estimate the power will be small, because no signal is incident from that di-

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[1] An input SNR of $0dB$ is a worst case assumption, because conventional detectors require an SNR in the order of $7 - 9dB$ for proper BER performance, which corresponds to an input SNR in the order of $0dB$ considering a maximum SNR gain of $10 \log_{10} M = 9dB$.

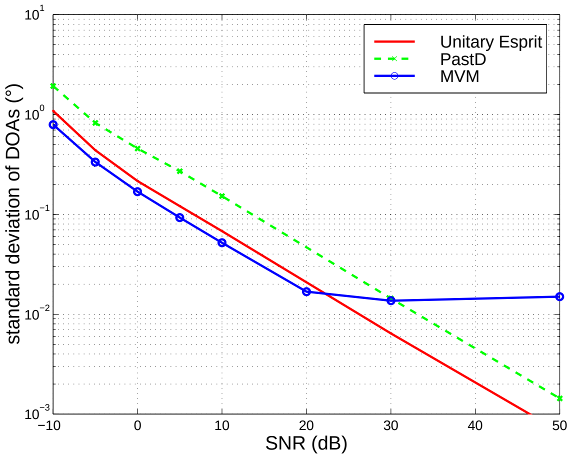

Figure 5: Simulated estimation accuracy of the **DOAE** versus SNR when a single plane wave is incident from $\phi = 0°$.

rection. Thus, the **ULpBF** will not try to place an unnecessary null in that direction.

V. BER PERFORMANCE IN AN AWGN CHANNEL

We measured the raw BER in an additive white Gaussian noise (AWGN) channel. The MS and the BS are linked via a traffic channel with no interferer present. BER measurements were performed over a period of $10s$ or 2000 bursts.

The demonstrator allows simultaneous processing of the *same* input data with a different algorithm. **A^{3}P**'s BER is referred to the BER of a single antenna. From Fig. 7 the expected gain in SNR of approximately $9dB$ compared to the single antenna is evident (Fig. 7). We applied **A^{3}P** in three different configurations, i.e. all three DOA estimators. The BER performance differs only slightly, as could be expected from the similar measured estimation accuracy.

VI. INTERFERENCE SUPPRESSION CAPABILITIES

To quantify interference suppression capability, we measured the raw BER of the MS with an interfering CW signal present. The user was positioned at 0° and had constant power with an input SNR of $7.5dB$. The interferer, with varying power, was located at $-19°$. As a reference we applied both, the single antenna and a scanning beam algorithm [17]. The scanning beam algorithm steers 128 regularly spaced, fixed beams and selects the signal corresponding to the beam that receives most power. Thus it gives satisfying BER only as long as the user signal is stronger than the interferer, i.e. for $C/I > 0dB$. In contrast, **A^{3}P** is much more robust against interference (Fig. 8). It gives a BER of 1% at an input C/I of $-6.5dB$.

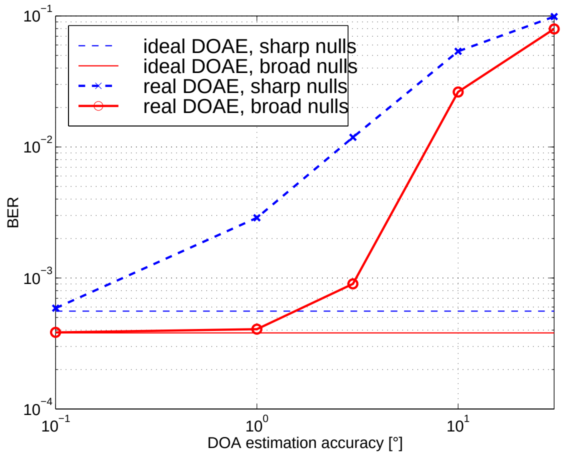

Figure 6: Effect of DOA estimation accuracy on the BER of the **A^{3}P**. The mean input C/I is $0dB$ and the mean input SNR is $20dB$ througout.

VII. CONCLUSIONS

The measurements have confirmed the principal functionality of **A^{3}P**. Beamforming with broad nulls improves the system's robustness in synthetic mobile radio channels. We conclude that the DOA estimation accuracy is not of great concern. Instead it is more important to prevent that far–off estimated DOAs are selected for beamforming [16].

In an AWGN channel, **A^{3}P** improves the tolerance to interference by $12dB$ versus the single antenna and nearly obtains the theoretical SNR gain of $9dB$ over the single antenna reference. With today available computing power the entire array processing run–time is only 1ms, allowing real–time adaptation of the antenna pattern *every* GSM frame.

Acknowledgment The authors thank Michael Hother and Guillaume de Lattre for carrying out the measurements.

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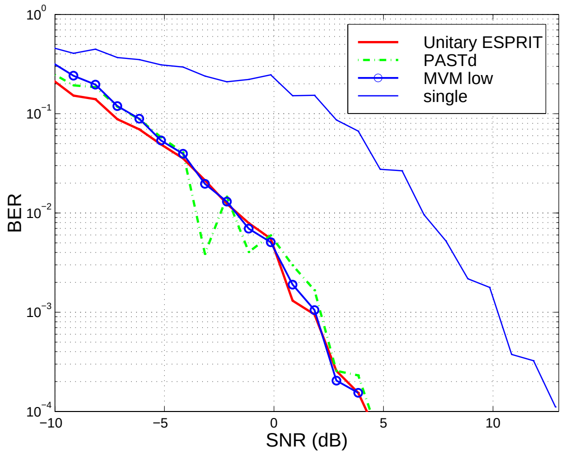

Figure 7: BER of the **A^{3}P** in a static channel. As reference the performance of a single antenna is plotted.

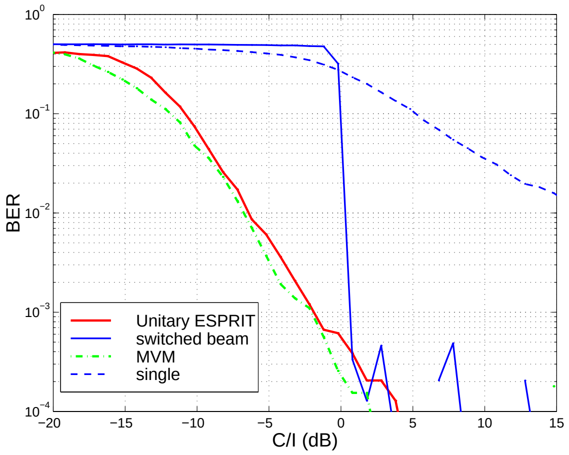

Figure 8: BER of the **A^{3}P** in a static channel with CW interferer. **A^{3}P** uses Unitary ESPRIT (solid thick line) and MVM (dashed thick line) as DOAE. As reference the performance of the scanning beam (solid thin line) and the single antenna (dashed thin line) is plotted.

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