Experimental Evaluation of an Adaptive Antenna for a TDMA Mobile Telephony System

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ABSTRACT

Measurements of an adaptive DCS-1800 base station antenna, used in uplink only, are presented and analysed. Both laboratory measurements and outdoor field trials have been performed. The antenna is improving the C/I ratio more than 30 dB. Calculations using measured data, assuming downlink performance equal to that of the uplink, show a spectral efficiency gain of 6 over present base station systems.

INTRODUCTION

The number of users in mobile telephony systems is dramatically increasing. A proposed method to increase the number of voice channels per available bandwidth and square kilometre is to introduce adaptive array antennas, where suppression of co-channel interferers and spatial multiplexing is made available.

A testbed project commenced 1994 at Uppsala University and Ericsson Radio Access AB. The aim is to evaluate and develop adaptive antenna technologies for mobile communication systems and to obtain experience using this technology in base stations. Other testbed projects have been reported in [1,2].

This report presents the adaptive base station antenna with two parallel receiving channels, using the Sample Matrix Inversion (SMI) -algorithm. Results of trials with spatial multiplexing is presented. Real DCS-1800 traffic data are used, and the output of the adaptive antenna can be connected to an ordinary base station RX for comparative BER measurements with an ordinary base station antenna.

I. ADAPTIVE ANTENNA ARCHITECTURE

The adaptive antenna is a test system which is intended to work in the uplink only. The antenna is designed for integration with an existing base station system (DCS-1800), at the frequency of 1.8 GHz. The adaptive antenna has two parallel receiving channels and trials with spatial multiplexing are then possible. Brief specifications of the adaptive array system are shown in Table I. The adaptive antenna is shown in Fig. 1 and schematic in Fig.2. The weighting and summing of the received signals are performed on the received RF signal to give the possibility to use an ordinary base station as a receiver. The base station TRX also transmits actual DCS-1800 data bursts to give the possibility to calculate BER and other parameters characterising the transmission. The TRX is also giving synchronisation signals to initiate sampling.

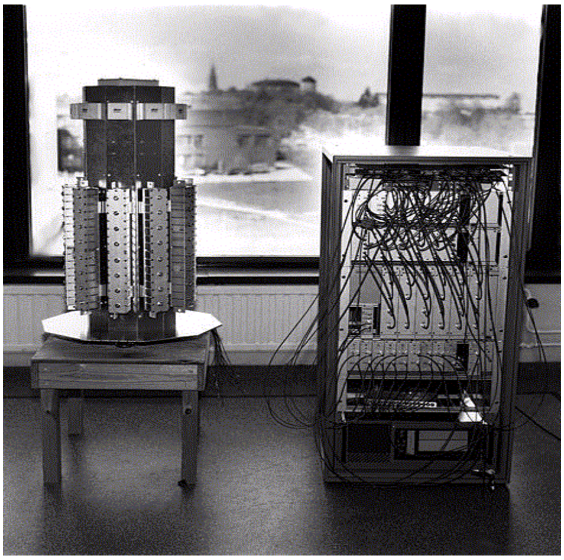


Fig. 1. The adaptive antenna, to the left the front end and to the right the rack with receivers, DSP-system and weighting units.

The RF signal is splitted and down-converted to the baseband and separated into I and Q channels where sampling at bit rate is done. The used SMI-algorithm uses three out of seven TMS320C40 signal processors and the training sequence of 26 bits in each DCS-1800 traffic channel burst is used as a reference signal.

A feedback receiver is placed after the summation for calibration of the system. Calibration takes place off-line, i.e. prior to operating the antenna system by injecting a CW signal through directional couplers after the antenna elements, see Fig. 2. By performing the calibration off-line, mismatches in the receiving channels are reduced and thus the array performance is improved [3]. Data from the calibration are stored as look-up tables in the DSP.

The weighting is performed on the RF signal using a phase shifter and an attenuator. The phase shifter accuracy is 1 degree and the attenuator is adjustable in 1 dB steps down to -50 dB.

TABLE I
SPECIFICATIONS OF THE SYSTEM

Item	Specification
Radio channel	
Center Frequency	1721 MHz
Modulation	GMSK *(BT=0.3)*
Adaptive array	
Number of elements	10
Configuration	Circular
Element spacing	0.56λ @ 1721 MHz
Polarisation	Vertical
Element beamwidth	80 degrees
Digital system	
DSP Processors	Seven TMS320C40
Sampling frequency per I- and Q-channel	270 kHz
ADC resolution	8 bit
ADC dynamic range	-32 dBm to -80 dBm
Algorithm for weight calculation	SMI
Weights	
Class	Analog
Phase shift resolution	1 degree
Amplitude attenuation resolution	1 dB

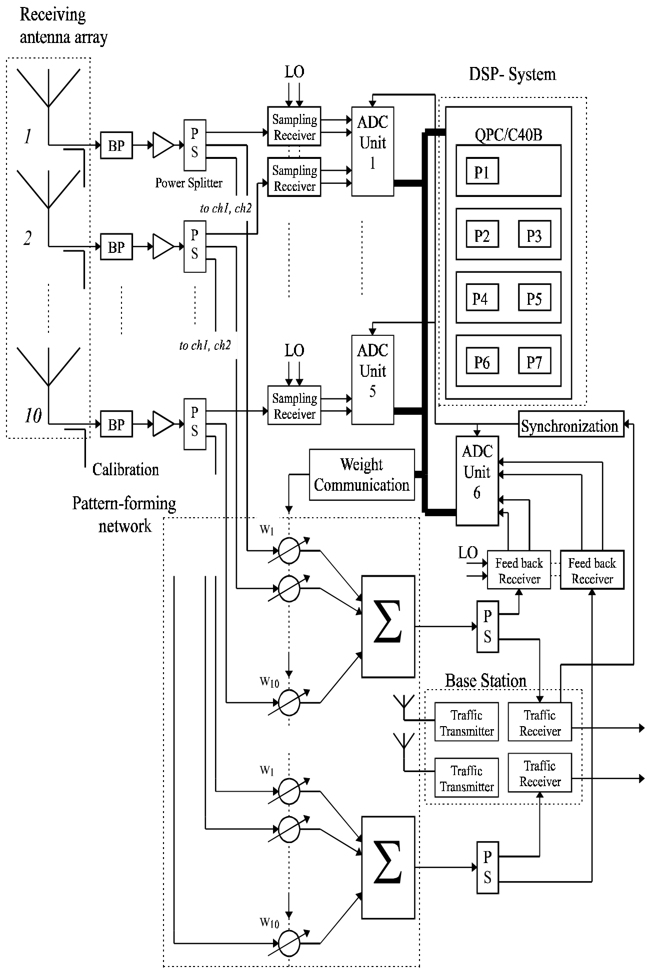


Fig. 2. Adaptive antenna architecture

II. MEASUREMENTS IN LABORATORY

To perform a measurement that verify the adaptive antenna performance in a laboratory, without introducing difficulties of multipath propagation and uncontrollable scattering the front end is replaced with an 8×8 Butler matrix that is fed by two signal generators, controlled by the basestation TRX. This give rise to a scenario similar to that of using an 8-element linear array of isotropic elements spaced λ/2 with DOAs (direction of arrival) -14.5° and 14.5° respectively relative to broadside. The outputs of the Butler matrix are then fed into the adaptive antenna receivers.

The performance of the adaptive antenna can be examined by measuring the output BER and output power of the carrier (C_{out}) and interferer (I_{out}) for different settings of input power (C_{in}, I_{in}). The interferer is a GMSK signal modulated with pseudo random (PRBS) data. The carrier C is GMSK modulated with actual DSC-1800 traffic channel data containing the 26 bit training sequence. Ten measurements were performed and the diagrams presented show the mean of these series, see Fig. 3. Fig. 3(a) shows the suppression of the interferer through the adaptive antenna system. The algorithm is able to suppress the interfering signal when the power of the interferer is in the ADC dynamic range. The ADC uses 8 bits giving a dynamic range of 48 dB thus below -80 dBm the interferer is hidden in noise and no suppression is possible. The interferer is suppressed to the quantisation noise floor if the spatial correlation is sufficiently low, which can be assumed here. This gives a larger suppression of strong interferers than of weak ones.

The dashed line surrounding the brightest area in Fig. 3(a) is the 20 dB iso-suppression line. The main contribution to the C/I improvement in Fig. 3(b) is from the interferer suppression, the carrier amplification was lower and approximately constant at about 2-6 dB for all carrier and interferer powers in the ADC dynamic range. With an interferer power at -40 dBm and the desired input signal power between -70 dBm and -40 dBm the adaptive antenna is improving C/I with more than 30 dB. When either of the signal levels exceeds the ADC dynamic range the C/I improvement by using the adaptive antenna is very low, even less than 0 dB giving a C/I degradation.

An other illustrative way of presenting the measurement data is to plot the improvement of the BER for different settings of C_{in} and I_{in}, see Fig. 3(c). The improvement is measured relative to one of the Butler matrix outputs, i.e. without using the adaptive antenna. Clearly the BER improvement is zero for C/I > 9 dB because the BER is zero for an ordinary base station receiver in this triangular area. This is the threshold level in DCS-1800 for 0 % BER. Above this triangle is the region where we benefit from using the adaptive antenna compared to using an ordinary base station antenna. Here BER improvement is up to 50% giving a BER out from the adaptive antenna of 0%. A C/I ratio above -20 dB is thus necessary to give a BER of 0% at this setup, using the Butler matrix. These measurements are after FEC (forward error correction) decoding of class Ib data in the base station.

(a)

(b)

(c)

Fig. 3. Measurements performed in laboratory, showing (a) suppression of interfering signal, (b) improvement in C/I and (c) improvement in BER using the adaptive antenna. Mean values from 10 measurements.

III. OUTDOOR MEASUREMENTS

A. Measuring area and experimental equipment:

The purpose of the field trials was to characterise the system and its performance in a controlled environment with few variable parameters, for in the next stage do urban measurements introducing problems of multipath propagation, fading, doppler spread etc. Therefore the adaptive antenna performance was investigated at the controlled antenna measuring site of FFV Aerotech in Arboga, Sweden. This antenna range measuring system is situated in open terrain. The adaptive antenna front-end was mounted on a rotational mount placing the circular array approximately three meters above ground, enabling 360 degrees azimuth rotation, see Fig. 4. A five meter horizontal bar was also mounted on the rotational mount on which a horn antenna was placed. A second horn antenna was placed 30 cm above ground, 20 meters away from the rotational mount, this to form constructive interference of direct wave and ground reflex at the location of the array antenna, avoiding a fading dip.

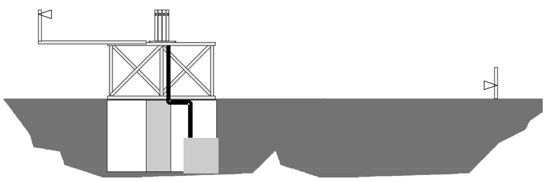


Fig. 4. Antenna range measuring system

The distance to the closest obstacles (trees) is about 500 meters providing a rather echo free environment. The horn antennas were fed by different signal generators, GMSK modulated with data from different base stations using different training sequences. All experiments were made at the frequency of 1721 GHz.

B. Radiation pattern measurements:

The angle between the interfering and desired signal was set by rotating the rotational mount. The antenna was then allowed to adapt on the signal environment before freezing the weights. During rotation the adaptive antenna was illuminated by a CW signal from the field antenna. The output power of the adaptive antenna was measured at angles from 0 to 360 degrees in steps of half a degree. The measurements were made for different angle separations and different power levels of the desired and interfering signals.

Fig. 5 shows the adapted radiation pattern of the second beamformer where the angle between the desired and interfering mobile is 90 degrees and they are of equal power. As can be seen a null is directed towards the interfering signal whilst we have a pointing error of the main beam. The interfering signal is however suppressed some 25 dB relative to the desired signal. The array pattern distortion, i.e. the pointing error of the main beam, is due to the short DCS-1800 training sequence. In [7] it is shown that the use of a short reference signal leads to a poorly estimated covariance matrix because of the slow sample convergence rate of the SMI-algorithm when the desired signal is present in the matrix.

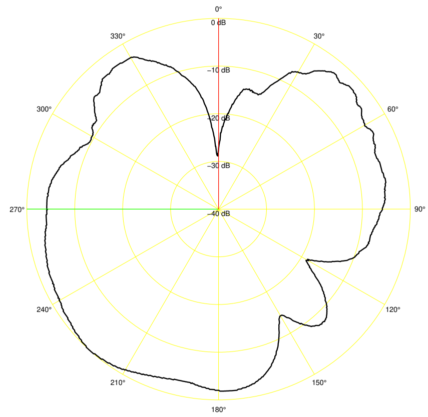


Fig. 5. Adaptive antenna radiation pattern. Desired and interfering signals of equal strength with DOAs of 270° and 0° respectively.

One way of dealing with the problem is to use the technique of diagonal loading, i.e. the adding of a small value to the diagonal elements of the matrix. With a perfectly estimated covariance matrix all noise eigenvalues will be identical and equal to the noise variance. A poor estimate gives non-identical eigenvalues resulting in a distorted pattern. By choosing the loading value larger than the noise eigenvalues but smaller than the eigenvalues of the desired and interfering signal the overall noise level is risen, resulting in almost identical noise eigenvalues [3]. The loading value L was therefore chosen as $L/\sigma^2 \sim 10^2$.

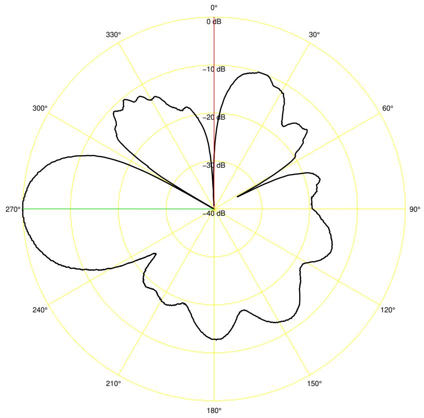
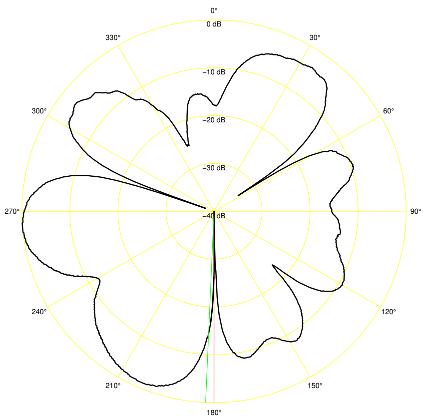


Fig. 6. Effect of diagonal loading.

The diagonal loading will decrease the SIR somewhat, but this is compensated by an increase in the SNR because of the lower sidelobe levels, leaving the SINR unchanged [7]. Fig. 6 shows the measured radiation pattern where the signal environment is the same as in Fig. 5 but the covariance matrix is diagonally loaded. As can be seen the pattern retains its null in the direction of the interfering signal, but now the main lobe points towards the desired signal and the sidelobe level is suppressed down to below -10 dB. Figs. 7(a) and (b) show radiation patterns of the two beamformers where the desired signal and interferer are separated 2.5 degrees. Note that the two signals impinging on the array play opposite roles in the two beamformers. Despite the small angle separation, the interfering signal is suppressed more than 20 dB relative to the desired signal in both diagrams. Note also the resemblance of the two diagrams outside the spatial region of interest. This indicates that apart from the opposite treatment of the two signals the beamformers see the same noise environment.



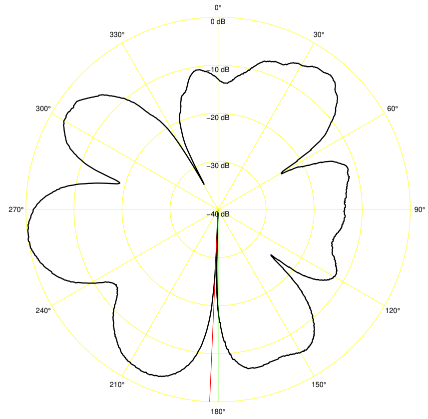


Fig. 7. Desired and interfering signals of equal strength with DOAs of 182.5° and 180°, respectively. (a) Beamformer one. (b) Beamformer two.

For every radiation pattern measured, also the suppression of the interferer and the amplification of the desired signal were measured. The results for $(C/I)_{in}$=-20 dB, where the absolute values of C and I are the same for every angle, are presented in Table II. It can be seen that the suppression of the interferer is rather independent of the DOA separation whereas the amplification of the desired signal decreases with decreasing DOA separation. This is a natural consequence of the limited beamwidth of the array, i.e. the most narrow beam possible with the actual array configuration is not enough to provide the peak towards the desired signal when a null is directed in the angle of the interferer.

TABLE II C/I IMPROVEMENT IN dB FOR DIFFERENT DOA SEPARATION C/I$_{IN}$=-20 dB			
DOA separation	Interferer suppression	Carrier gain	Improvement in C/I
180°	31	2	32
135°	30	4	34
90°	30	4	34
45°	32	2	34
10°	29	2	31
5°	27	-10	17
2.5°	26	-8	18

C. BER for different DOA separation between interferer and carrier:

The BER was logged from the base station TRX while rotating the antenna giving BER as a function of DOA separation between interfering and desired signal sources. These measurements were made for different ratios of C/I, see Fig. 8. The transition between a BER of 0% and BER of 50% is very sharp as is characteristic for a digital communication system. For C/I ≥ -10 dB the minimum angle separation for 0% BER is less than 4 degrees and for decreasing C/I ratios this minimum angle increases

The BER output is a consequence of the output C/I and depends on the base station RX detection properties. However the minimum angular separation is an important parameter when calculating the spectrum efficiency gain using adaptive antennas in base stations.

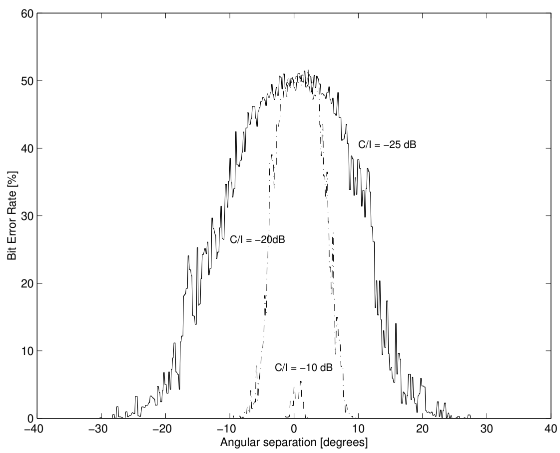


Fig. 8. BER (after FEC decoding of class Ib data) as a function of interferer and desired signal DOA separation in horizontal plane.

For C/I ≥ 0 dB a BER of 0% was measured although the plane waves impinging on the array only differed in elevation angle (same azimuth angle)! This can be explained by the vertical beamforming of the circular array, i.e. plane waves with the same azimuth angle but with different elevation angles give rise to different spatial signatures (=array response vectors) at the array. For practical reasons the two illuminating antennas were positioned at different heights as can be seen in figure 4, giving a separation in the elevation plane of approximately eight degrees. Different spatial signatures and low correlation between the training sequences of the two signal sources are enough for the adaptation algorithm to separate the signals.

IV. BENEFITS OF ADAPTIVE ANTENNAS FOR CELL ARCHITECTURES

The introduction of adaptive base station antennas gives the possibility to transmit and receive electromagnetic energy towards/from co-cell users sharing the same frequency and timeslot. This is the fully developed SDMA (spatial division multiple access) method which operates on top of a traditional F/TDMA scheme. An important figure of merit when introducing adaptive antennas is the spectrum efficiency γ defined as the number of users per MHz of bandwidth and km^2:

$$\gamma = \frac{T}{B \cdot S \cdot A} \tag{1}$$

Here T is the average traffic load in Erlang, A the cell area in km^2, S the number of cells in a cluster and B the bandwidth required to serve the users in a cluster (total available bandwidth of the system). If we assume hexagonal cells, omnidirectional antennas and a fourth-power law for the signal levels (signal powers ~r^{-4}, r distance from the base station) the cluster size S can be written as

$$S = \frac{1}{3}\sqrt{K\frac{C}{I}} \tag{2}$$

where C/I is the carrier-to-interference ratio caused by K effective first tier co-channel interferers, see [6].

Now assume introduction of adaptive antennas with N spatially multiplexed channels (parallel beams) in a traditional system (trad). This allows us to reduce the cluster size S keeping the cell area, cluster bandwidth and requirements of carrier-to-interference ratio unaltered. The spectral efficiency gain of introducing adaptive antennas can then be stated as:

$$G = \frac{\gamma_{SDMA}}{\gamma_{trad}} = \frac{T_{SDMA} S_{trad}}{T_{trad} S_{SDMA}} \tag{3}$$

Now assume that the following holds:

$$T_{SDMA} = NT_{trad} \tag{4a}$$

$$K_{SDMA} = \frac{b}{\pi} NK_{trad} \tag{4b}$$

i.e. increasing the traffic load (4a) N times will also increase the number of interferers by a factor N (4b). The number of interferers will however be decreased by a factor bπ^{-1}, where b is the minimum separation allowed. b is a function of the input carrier-to-interference ratio at the base-station-site, see figure 8. The factor $b\pi^{-1}$ represents the spatial filtering of the array antenna. Only interfering signals closer in angle than b radians from the desired mobile will be counted as interferers. So, conclusive, the spectral efficiency gain in this simple model can be calculated using (2,3,4) as:

$$G = \sqrt{\frac{N\pi}{b}} \qquad (5)$$

SDMA requires a minimum C/I ratio at the input of the base station antenna to make signal detection possible. Assuming a minimum C/I ratio of -20 dB, still providing a BER of 0%, gives a minimum carrier-to-interference separation of 10 degrees, i.e. $b=\pi/18$ radians (see Fig. 8). Assuming a downlink with similar performance as the uplink gives us an opportunity to calculate a hypothetical spectral efficiency gain. The spatial multiplexity in our system is N=2 which gives, using (5), a spectral efficiency gain G = 6 which is a significant improvement over a traditional system.

The minimum C/I ratio is dependent on two main parameters [4]. The first is the angular separation of the mobiles and the second is the power levels received at the basestation from the mobiles, which is dependent on the distance between the mobile and the basestation and the individual mobile power control. Power levels arriving at the base station can typically vary as much as 50 dB due to the limited dynamic range of DCS (GSM) power control [5]. It is convenient for users sharing the same channel to have similar power levels because the SDMA implementation can only attenuate co-channel users up to a given level. A proposal in [6] is to group mobile users into power classes which limits the received C/I ratio. Introducing power classes reduces the overall SDMA gain G, but the reduction is small and a significant gain over traditional systems is still obtained.

V. CONCLUSIONS

The laboratory tests show that the adaptive antenna presented here is capable of improving the C/I ratio more than 30 dB when the desired signal is weak and in the presence of a strong interferer. When the angle between the desired and the interfering signal is decreased the C/I improvement is reduced, mainly due to a loss in carrier gain. With C/I=-20 dB the minimum separation between the desired and the interfering mobile for an error-free transmission is 10 degrees. It has been verified that diagonal loading is a way to improve the estimation of the covariance matrix, giving lower sidelobes and a distinct mainlobe towards the desired signal. Assuming an existing downlink, a comparison with a traditional base station antenna gives a spectral efficiency gain of G=6, thus a significant improvement over existing base station systems.

This report has demonstrated the feasibility of using adaptive antennas at base stations for mobile communication networks. Future measurements using this antenna includes the behaviour in a more realistic signal environment with additional problems of fading and doppler spreading.

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