DESIGN AND EVALUATION OF A FULLY ADAPTIVE ANTENNA FOR TELECOMMUNICATION SYSTEMS

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ABSTRACT

An adaptive antenna for the DCS-1800 mobile telephony system has been designed and evaluated. The antenna is working in uplink only and has a multiplexity of two channels per frequency and timeslot. The array antenna has a circular structure and the complex weights are calculated using the sample matrix inversion method (SMI). Evaluations of the adaptive antenna in an outdoor environment show promising improvement of the carrier-to-interferer-ratio (C/I) of more than 30 dB. Measurements of bit-error-rate (BER) for different angular separation of the mobiles show that for an input C/I ≥ -10 dB the minimum angular separation for approximately 0% BER is less than 4 degrees.

INTRODUCTION

The use of adaptive antennas in mobile communication systems offers a possibility to increase the system capacity. To exploit the benefits of using adaptive base station antennas, a testbed project commenced 1994 consisting of groups at the Signals and Systems group at Uppsala University and Ericsson Radio Access AB. The project is financed by NUTEK and Ericsson Radio Access AB. Other testbed projects are reported in [1,2]. The aim is to evaluate and develop adaptive antenna technologies for mobile communication systems and to obtain experience using this technology in base stations. The testbed was completed in autumn 1996 and has been evaluated at the FFV Aerotech AB antenna measurement range in Arboga, Sweden. The testbed is designed for DCS-1800 and in receiving (uplink) mode only. The output from the antenna can be connected to an ordinary DCS-1800 basestation transceiver to perform realistic transmissions of actual DCS-1800 signals. This gives the possibility to in an easy way measure the improvement in bit error rate (BER) using the adaptive antenna in various signal environments.

This report briefly present the architecture of the antenna and results from the field trial measurements. The aim is to show that adaptive antennas are possible to use in the uplink for a F/TDMA system to enhance the system efficiency. The downlink problem is not addressed here and is a more challenging task due to the frequency duplex distance between uplink and downlink (the frequency duplex distance in DCS-1800 is 95 MHz). This makes the impulse response of the downlink hard to estimate from the information in the uplink transmission [3]. A proposed method in a 3rd generation cellular protocol is to use feedback of information from the mobile station (MS) to the base station (BS) so an useful estimate of the channel can be made [4].

However, with no fully developed downlink algorithm, the use of the adaptive antenna as a spatial filter for interference reduction (SFIR) is an excellent way to enhance the carrier-to-interferer ratio (C/I) as shown in this report.

ADAPTIVE ANTENNA ARCHITECTURE

The adaptive antenna is able to receive signals from two MS allocated to the same DCS-1800 timeslot and frequency by letting beamformer no. 1 suppress signals from MS no.2 while directing a maxima in the radiation pattern against MS no.1, and vice versa for beamformer no. 2. The primary purpose of the beamforming is to improve C/I, by suppression of the other MS transmitting on the same frequency and timeslot and also suppression of other interfering sources. A secondary purpose is to improve the carrier-to-noise ratio (C/N) by increasing coverage due to beamforming. The architecture of the adaptive antenna can be seen in fig. 1.

The antenna array consists of ten patch antenna elements in a circular arrangement and the beamwidth of the patch elements is 80 degrees. The antenna element spacing is 0.56 wavelengths at 1.721 GHz. This arrangement gives full horizontal coverage with a practically equal antenna aperture in all directions. Each antenna element is followed by a front end unit which filters and amplifies the antenna signal. After the front end units the signals are distributed to the sampling receivers, and the two beamformers, respectively. The task of the beamformers are to weight (both amplitude and phase) and sum the signals from each front end. The output from the beamformers will thus be spatially filtered. Note that the weighting of the signals takes place at the carrier frequency and the benefit of this is the availability to connect the adaptive antenna to a DCS-1800 base station TRX for comparison measurements with an ordinary BS antenna and to perform voice quality tests using standard DCS-1800 cellular telephones.

The output signals from the beamformers is also distributed to the feed back receivers and allows the DSP to measure the differences in complex amplitude between the antenna element channels respectively and also between the weight and sampling receiver in each antenna channel. This calibration takes place off-line, i.e. prior to normal operation. The DCS-1800 TRX performs the demodulation. The demodulated data is used for measuring the bit error rate for evaluation purposes.

To distinguish between the mobiles some rules of assigning *training sequences* and *frequencies* as well as *time slots* to the mobiles must exist. Any two mobiles having the same set of the three parameters above will interfere with each other (assuming they share the same cell). The beamformers will be used to discriminate between the different training sequences. The two DCS-1800 TRX:s are coherently transmitting two DCS-1800 TCH (Traffic Channel) bursts on the same frequency and timeslot but with different training sequences. Calculation and weight setting takes 3.1 ms so the two radiation patterns corresponding to the two spatial multiplexing channels are updated each frame (a DCS-1800 frame is 4.615 ms).

The TRX gives synchronisation signals to the DSP system for initiating sampling and down conversion to baseband. The sampling frequency is 270 kHz for each quadrature signal. The A/D converters uses 8 bits giving a dynamic range of 48 dB. The choice of 8 bit A/D converters is a consequence of the 32-bit DSP data bus. These 8-bit words are collected by the DSP in order to calculate the weights using the SMI-algorithm (Sample Matrix Inversion) implemented in three TMS320C40 signal processors. SMI was chosen because of fast convergence rate [5] and the accessibility to a powerful DSP system to cope with the heavy computational load.

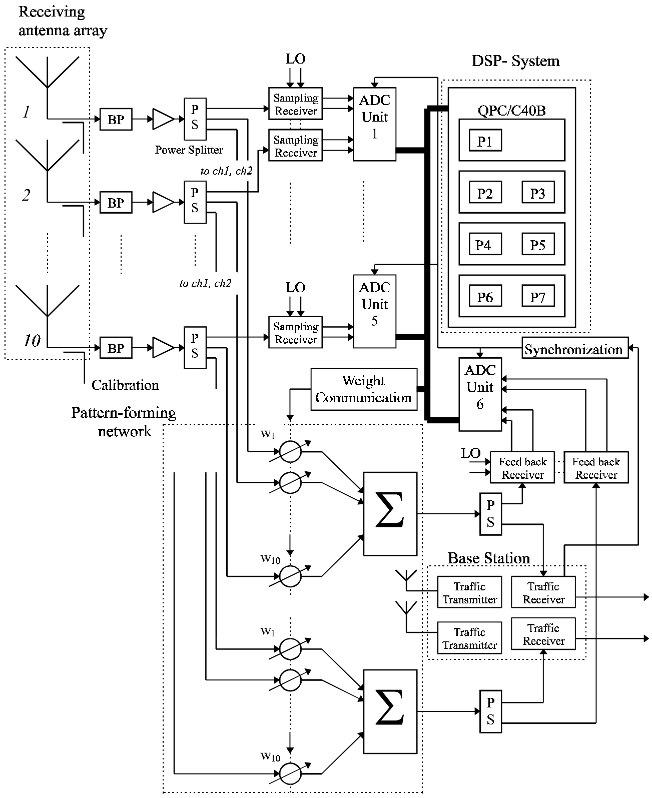


Fig. 1. Adaptive antenna architecture

The covariance matrix of the input vector **x** (where **x** is a 10×1 matrix with elements corresponding to the signal of each antenna element) is defined as **R** = E{**xx**^{H}} where E denotes expectation and H complex transpose. The steering vector is defined as **p** = E{**x**r*} where r is the reference signal and the asterisk denotes complex conjugation. A straight forward way of estimating **R** and **p** is to use

$$\hat{\mathbf{R}} = \frac{1}{N}\sum_{i=1}^{N}\mathbf{x}_i\mathbf{x}_i^H$$

$$\hat{\mathbf{p}} = \frac{1}{N}\sum_{i=1}^{N}\mathbf{x}_i r_i\,*$$

where $\mathbf{x}_i$ is the *i*:th snapshot of the input vector and r_i is the *i*:th symbol of the reference signal. The two first symbols of the 26-symbol DCS-1800 training sequence are for practical reasons not used, i.e. N=24. Using these estimates to calculate the weights is known as the SMI-algorithm. The optimum weight vector is given by $\mathbf{w} = \mathbf{R}^{-1}\mathbf{p}$ [6]. The estimated optimal weight vector would therefore be $\hat{\mathbf{w}} = \hat{\mathbf{R}}^{-1}\hat{\mathbf{p}}$, which is solved in the DSP by Gaussian elimination with backsubstitution. This method is both faster and more accurate than calculating the inverse of the covariance matrix and applying it to the steering vector [7]. The analog weights are adjusted using 12 bits for the phase and bits for the amplitude control giving an accuracy of 1 degree in phase and 1 dB in attenuation down to -50 dB.

MEASUREMENT SITE AND MEASUREMENT PROCEDURE

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.

The measurement site is situated in open terrain providing a rather echo free environment. By mounting the experimental antenna on a rotational mount together with one of the illumination antennas, arbitrary azimuth angle separations can be investigated and the radiation pattern of the experimental antenna be measured in a simple manner. The antenna measurement site is illustrated in Fig. 2. A more thorough treatment of the measurement site and the measurement procedure is presented in [8].

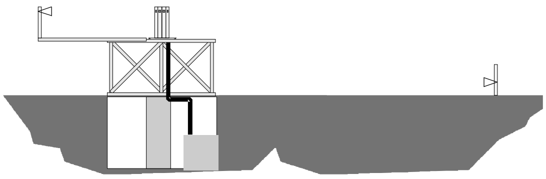


Fig. 2. Antenna measurement system. The adaptive antenna front-end is positioned on a rotational mount together with one of the two illumination antennas (mounted on a horizontal bar). The other illumination antenna is placed on the ground. Below the rotational mount the rack unit of the adaptive antenna, signal generators and measuring equipment are kept.

RADIATION PATTERN MEASUREMENTS

Several measurements were made for different angular separations and different power levels of the desired and interfering signals. Fig. 3(a) and (b) show the radiation patterns of the two beamformers where the equi-powered desired and interfering signals are separated 90°. Both beamformers direct a null towards the interfering signal (note that the two signals play opposite roles in the two beamformers). We have however no distinct beam pointing towards the desired signal. This is due to the poor estimate of the input covariance matrix [9], caused by the short DCS-1800 training sequence, and the fact that the desired signal is present in the input samples used to estimate the matrix. Though, comparing the received power in the two directions of interest gives at hand an improvement of the carrier-to-interferer-ratio (C/I) of some 30 dB. The difference in null-depth between the two beamformers is mainly due to the angular resolution when measuring the radiation patterns (the narrow null is more likely to be detected with a smaller angular resolution). Fig. 3(c) and (d) show the radiation patterns of the two beamformers for a DOA separation of 2.5°. This time however we have no hope of placing a null towards the interferer and at the same time direct the main beam towards the desired signal, because of the rather wide (>50°) 3 dB beamwidth of the array antenna. Naturally this leads to a lower increase in C/I relative to the case of 90°-separation. We have however an increase in C/I of about 20 dB.

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 power of C and I are held constant for every angle, are presented in Table I. 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 due to the above mentioned beamwidth of the array antenna.

The optimal improvement in C/I is limited by the presence of the quantisation noise floor corresponding to the 8-bit A/D converters used to sample the input base band signals. The interferer can not be suppressed more than down to the noise floor. A weak interferer (close to the noise floor) will therefore result in a lower increase in C/I relative to the case of a strong interferer, keeping the power of the desired signal constant. This however is not a problem, since with a high C/I on the input we have no need for a great increase on the output.

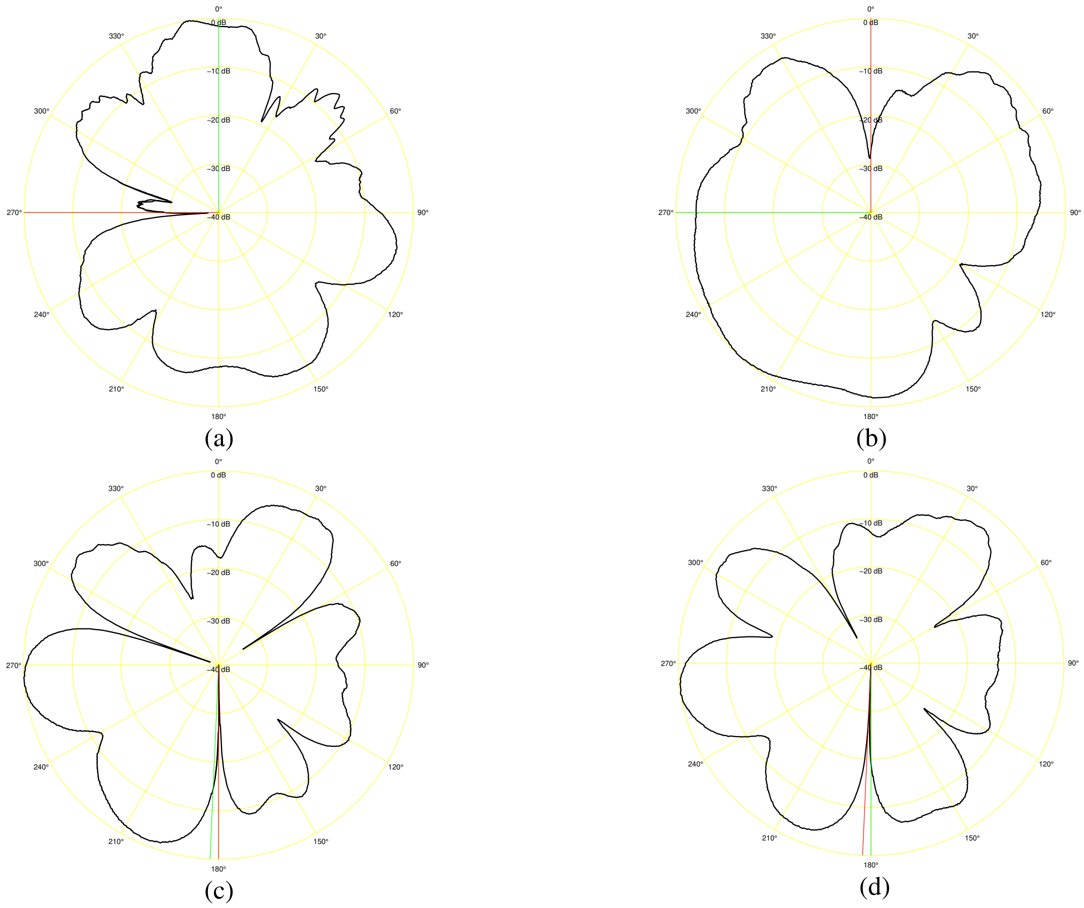


Fig. 3. Measured magnitude radiation patterns for different DOA separations. Desired and interfering signals are of equal strength in all diagrams. (a) Desired signal in 0°, interfering signal in 270°, beamformer 1. (b) beamformer 2. (c) Des. 182.5°, int. 180°, beamf. 1. (d) Beamf. 2

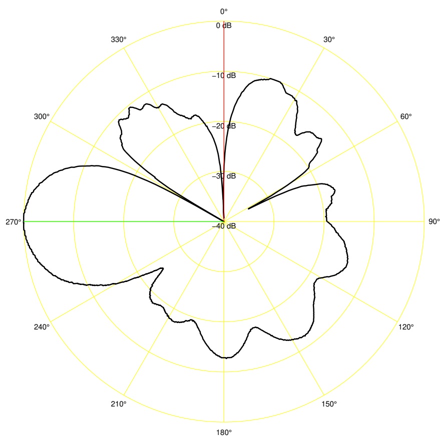
TABLE I

C/I improvement in dB for different DOA separation. $(C/I)_{IN}$=-20 dB.

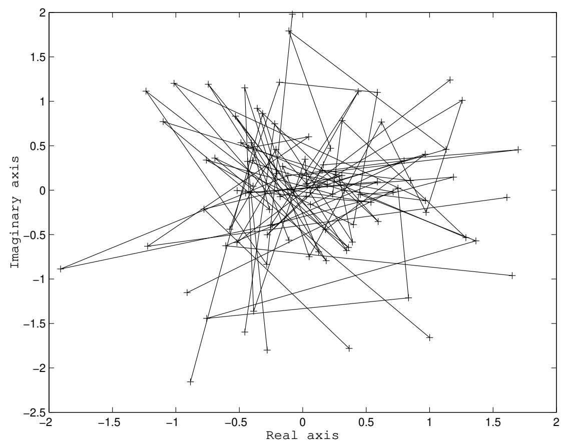
DOA separation	Interferer suppression	Carrier gain	Improvement in C/I
180°	31	2	32
135°	30	4	34
90°	30	4	34
45°	32	2	34
10°	29	2	31
5°	27	-10	17
2.5°	26	-8	18

One way of dealing with the lack of a distinct main beam and the large sidelobes 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 [10]. The loading value L was therefore chosen as $L/\sigma^2 \sim 10^2$.

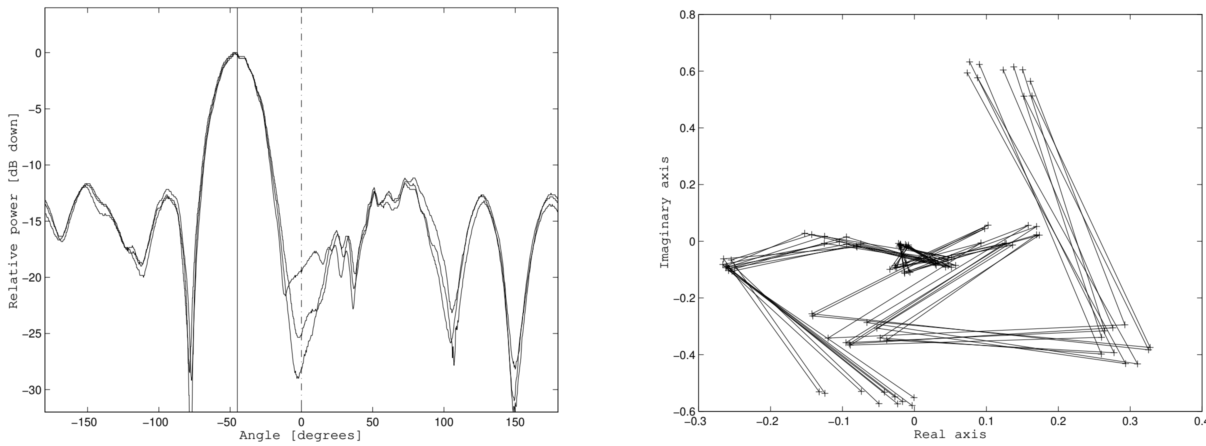
Fig. 4(a) shows the measured radiation pattern where the signal environment is the same as in Fig. 3(b) but the covariance matrix is diagonally loaded. As can be seen the pattern retains its null in the direction of the interfering signal, but now the main lobe points towards the desired signal and the sidelobe level is suppressed down to below -10 dB.



(a)



(c)



(b) (d)

Fig. 4. Diagonal loading. (a) Measured radiation pattern using diagonal loading. Desired signal in 270°, interferer in 0°, beamformer 2. (b) Three radiation patterns adapted on the same signal environment but at different time instances (using diag. load.). (c) Ten weight settings (diag. load. not used). Weights corresponding to the same setting are connected with a line. (d) Weight settings using diag. load.

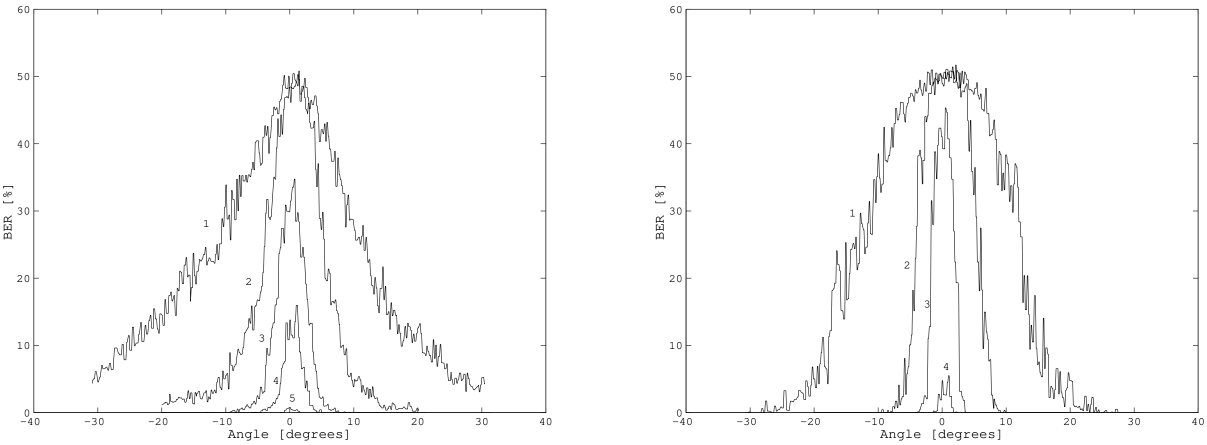
The use of diagonal loading can be seen as a way of increasing the convergence rate of the estimated covariance matrix [9], i.e. fewer samples are needed to get a fairly good estimate. Fig. 4(c) shows ten weight settings (ten elements per setting) in the complex plane calculated based on unloaded covariance matrices. These weight settings are completely different, indicating that the 26 snapshots used to estimate the covariance matrix is not enough for convergence. Fig. 4(d) shows ten weight settings corresponding to diagonally loaded matrices. These settings are practically identical and indicates that the number of snapshots in this case is sufficient to get a good estimate of the covariance matrices. Three measured radiation patterns adapted (using diagonal loading) on the same signal environment but at different time instances are shown in Fig. 4(b). As expected, because of the almost identical weight vectors, the radiation patterns are very similar.

BER-MEASUREMENTS FOR DIFFERENT DOA SEPARATION OF 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 and the DCS-1800 TRX presents the BER of the protected (class Ib) and unprotected (class II) bits (in DCS-1800, there are three levels of forward error correcting coding, the lowest level class II is unprotected bits and class 1b is rate ½ convolutional coded), see Fig. 5. The BER is calculated over a finite set of bits (26-multiframe) which implies that an error probability $\leq 0.5*10^{-3}$ is presented as 0%. The transition between a BER of approximately 0% and BER of 50% is very sharp as is characteristic for a digital communication system. For C/I $\geq$ -10 dB the minimum angle separation for approximately 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. The spectrum efficiency is defined as the number of users per MHz and km^2. In a SDMA system, this minimum angle determines the separation of MS when it is necessary for the BS to initiate an intra-cell handover, i.e. change timeslot or frequency of one of the MS.

With C/I ≥ 0 dB a BER of approximately 0% was measured at zero DOA separation. This is an effect of the measurement arrangement and could be explained by investigating the vertical beamforming of the circular array which allows the desired and interfering source to be located at the same horizontal angle but with different angles in the vertical plane as seen in Fig. 2.



(a) (b)

Fig. 5. BER as a function of interferer and desired signal DOA separation in horizontal plane.
(a) Unprotected (Class II) bits. (b) Protected (Class Ib) bits.
C/I=-25 dB (1), -20 dB (2), -15 dB (3), -10 dB (4), 0 dB (5).

CONCLUSIONS

The improvement of C/I for a DCS-1800 standard system using this specific circular adaptive array antenna has been quantified. The adaptive beamforming has been shown to improve C/I by 30 dB when an interferer is present with a power level equal to or higher than the carrier power. If the interferer is weak, the C/I improvement is lower, due to the quantisation in the A/D converters. Thus the number of bits used in the A/D converter is an important number when suppressing weak interferers.

The BER as a function of separation between two mobile stations using the same frequency and timeslot has been measured. The adaptive antenna is capable of suppressing a 15 dB stronger interfering signal located 10 degrees in angle from the desired signal source and gives an output BER of approximately 0 %. In a SDMA system the near-far effect and the fading margin imposes additional constraints on the minimum angle allowed between two mobile stations until an intra-cell handover must be initiated.

It has been verified that diagonal loading is a way to improve the estimate of the covariance matrix when the number of samples used is low. The use of diagonal loading lowers the sidelobe levels at the expense of a small loss in C/I improvement. Low sidelobe levels is of greater importance in a downlink implementation, where the spreading of interfering noise must be kept low.

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 an more realistic signal environment with additional problems as fading and Doppler spreading.

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