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Intelligent Antennas for DS-CDMA Systems

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Abstract: This paper considers the performance of a DS-CDMA system which employs adaptive antenna technology at the basestation site. By utilising the capability of ray-tracing to provide the complex channel impulse response, a new ray-based simulation methodology for an adaptive antenna in a DS-CDMA system is presented. Results for a typical microcellular environment highlight the behaviour of the adaptive antenna. Finally, with the help of a DS-CDMA capacity analysis, the potential spectrum efficiency enhancement is evaluated and the improvement of some of the statistics of the system is discussed.

I. INTRODUCTION

The need for mobile radio systems with increased spectrum efficiency is paramount in the drive towards third generation systems [1-2]. Currently favoured solutions in today's systems, which are generally applicable to any modulation scheme or access technique, include the deployment of smaller cells as well as fixed sector, or multi-beam antennas at the basestation site. In terms of modulation schemes and access techniques the application of spread spectrum modulation techniques with Code Division multiple access (CDMA) and especially Direct Sequence (DS) CDMA is one of the currently favoured approaches.

Adaptive or intelligent antenna systems are currently receiving considerable attention as a means of increasing the spectrum efficiency of wireless networks [3-9]. Here the application of this technology is considered at the basestation site to support spatial separation of the spectrally and temporally overlapping mobile users. This can be exploited in a number of ways in a system employing DS-CDMA as the air interface technique [10], e.g. support mixed cell architectures, mitigation of the near-far effect and support of high data rate services

In this contribution the focus is on using the adaptive antennas in a microcellular environment with DS-CDMA. The work includes the development of a new detailed ray-tracing based simulation model for the adaptive antenna, combined with the calculation of the capacity improvement of a DS-CDMA system through Monte-Carlo simulation.

II. AN ADAPTIVE ANTENNA FOR SMALL CELLS

The angle of arrival (AOA) of the radio signal, along with its multipath components, directly affects the degree of spatial selectivity that can be exploited by the antenna system, i.e. whether to form a single narrow beam (direction finding), or adopt an optimum combining approach. With optimum combining, the basestation antenna optimises the weights in order to enhance the overall output signal-to-interference ratio. This ideally corresponds to maximising the gain in the desired directions and placing nulls in the directions of the interference, with the maximum number of nulls determined by the number of elements in the array. Nevertheless, in a microcellular environment, the angular spread of the signal from a single user is very wide due to the lower height of the BS antenna and the close proximity of the scattering objects, and also, the AOA of the signals changes rapidly, with the dominant direction not always towards the desired user, as in a large cell case. The above effectively imply that the ideal solution for an adaptive antenna, becomes now an optimisation problem. For the direction finding approach, due to the relatively low values for the delay times among the multipath signals in a microcellular narrowband DS-CDMA system [11], unless additional techniques which complicate even further the problem and are not always stable, are considered [12], performance degradation will occur.

All the above indicate that in a harsh environment like the microcellular environment, the optimum combining approach appears to be more flexible, providing increased capacity as well as the ability to adapt to the changing environment, as it will be shown in the following sections.

III. SIMULATION MODEL

The simulation model can be separated into three basic blocks, as it is shown in figure 1:

a) *Multipath Channel Model:* Impulse responses from the environment under investigation are generated using a ray- tracing simulation tool [13]. The input parameters to this tool include a geographical data base of the service area, the number of reflections, transmissions and diffractions, the transmitted power, antenna radiation

patterns etc. The output file includes the electric field, the time delay and the angle of arrival of the four most dominant received rays from each user.
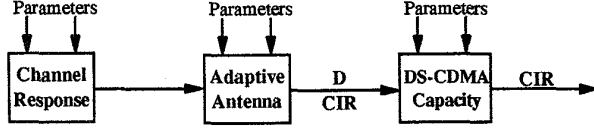

Figure 1: Simulation model block diagram

b) *Adaptive Antenna Array:* The type of adaptive antenna that is considered here, is an antenna array that is capable of modifying its radiation pattern, frequency response and other parameters by means of internal feedback control while the antenna system is operating, so as to maximise the signal-to-noise ratio of some desired signal which is received in the presence of noise and interference, at the receiver output.
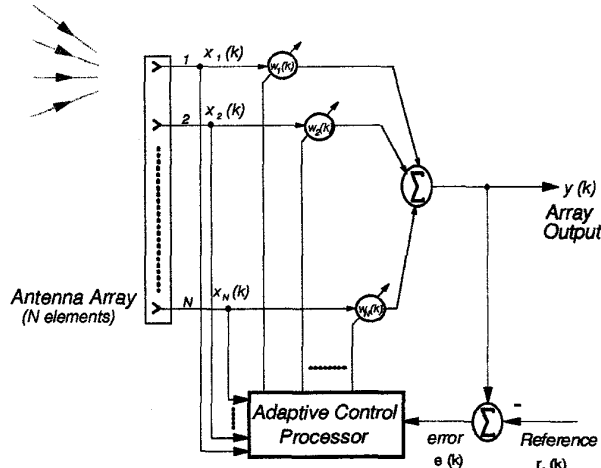

Figure 2: Adaptive Antenna Array

A block diagram for an adaptive antenna array is shown in figure 2, where:

$x_n(k)$ is the sample of the total received signal at the nth element at instant $t = kT$, where T is the sampling interval, as well as being the chip duration of the PN sequence and k is the sample number. $x_n(k)$ consists of the desired and interfering DS-CDMA signals and random noise, and it can be expressed as:

$$x_n(k) = \sum_{m=1}^{M}\sum_{r=1}^{R} h_{mr} e^{jk_u d(n-1)\sin(\vartheta_r)} r_m(k-t_r) + N(k), \quad (1)$$

where h_{mr} and $r_m(k)$ are the elements of the vectors of the impulse response and the DS-CDMA signal from the mth user respectively:

$$\mathbf{h}_m = \left[h_{m1}, h_{m2}, \cdots, h_{mr}, \cdots, h_{mR} \right]^T,$$

$$\mathbf{r}_m = \left[r_m(k), r_m(k-t_1), \cdots, r_m(k-t_r), \cdots, r_m(k-t_R) \right]^T$$

$r_m(k) = \mathbf{d}_m(k) \cdot \mathbf{PN}_m(k) \cdot e^{j\xi_m}$, with $\mathbf{d}_m(k)$ the binary data and ξ_m the carrier phase of user m. $N(k)$ represents the random Gaussian noise. M is the total number of users, R is the total number of rays, d is the interelement distance, k_u is the wave number, ϑ_r and t_r are the angle of arrival and the delay of each ray and $[\ ]^T$ denotes the transpose. Although the total received signal at the nth antenna element is calculated by considering the interelement phase shift for each incoming ray, i.e. $(n-1)kd\sin(\vartheta_r)$, depending on the environment under investigation, it can also be calculated directly from the ray tracing tool.

The output from the adaptive array in vector notation is: $y(k) = \mathbf{w}^T(k)\mathbf{x}(k)$, where $\mathbf{w}(k)$ and $\mathbf{x}(k)$ are the weight and element vectors respectively. Using (1), this gives:

$$y(k) = \sum_{n=1}^{N} w_n(k)\left\{ \sum_{m=1}^{M}\sum_{r=1}^{R} h_{mr} e^{jk_u d(n-1)\sin(\vartheta_r)} r_m(k-t_r) + N(k) \right\}$$

where N the total number of antenna elements. The desired or reference signal $r_0(k)$ is simply the PN sequence from one user, and the error signal is defined as the difference between the array output and the desired signal $e(k) = y(k) - r_0(k)$.

c) *DS-CDMA Capacity Analysis:* Based upon the Monte-Carlo technique described in [14], a simulation model was used for the capacity calculations of the DS-CDMA system. The basic idea behind this kind of simulation is to generate a large number of random deployments of mobile users under realistic loading conditions. Using the co-ordinates of the basestation antennas, it is then possible to assign mobiles to base stations. The decision is based upon the shadowing and path loss experienced, and the selected basestation is the one which maximises the received signal power. For each deployment, a carrier-to-interference ratio SIR can be calculated and after many runs the complete cumulative distribution function of the SIR values can be produced. Given the SIR threshold for a particular BER requirement, the outage probability can then be generated, i.e. the percentage of time that the SIR falls below the given threshold. A commonly accepted value which determines the capacity of the DS-CDMA system is 1% outage. The total interference seen by the central basestation due to both the in-cell and the out-of-cell interferers, is:

$$I_{tot} = \int_{0}^{(2Tiers+1)R_{mic}} \int_{0}^{2\pi} \frac{P(l,\varphi)}{\pi R_{mic}^2} D(\varphi) r l dl d\varphi = \frac{I}{D}$$

where *Tiers* is the number of tiers of cells considered in the simulation, R_{mic} is the microcell radius, $P(l,\varphi)$ is the power transmitted by a user at distance l from the central basestation and angle φ, I is a constant which represents the value of the total interference seen by the BS before the spatial analysis is considered and D is the directivity of the BS antenna which is assumed omnidirectional in the vertical plane.
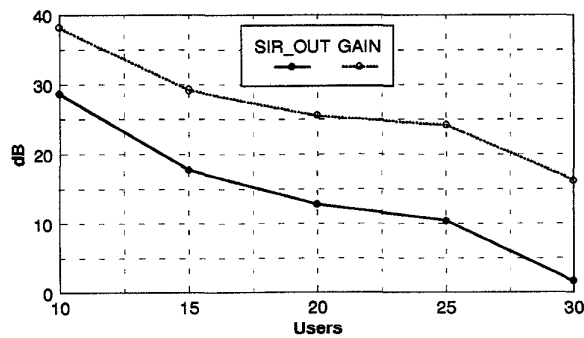
3. RESULTS

The model for the adaptive antenna offers the capability of selecting one from several adaptive processing algorithms. Table 1 summarises the parameters used in the simulations. In addition, each user in the simulation is stationary and ideally power controlled by the basestation.

Runs	5
Samples	500 or 1000
Array elements	8
Interelement spacing	$\lambda/2$
PN Length	255 chips
Algorithms	LMS-NLMS-RLS-SQRLS-DMI
Step (LMS-NLMS) [15]	0.005
Forgetting Factor [15]	1

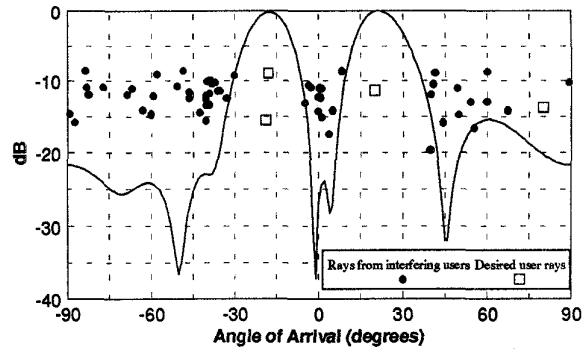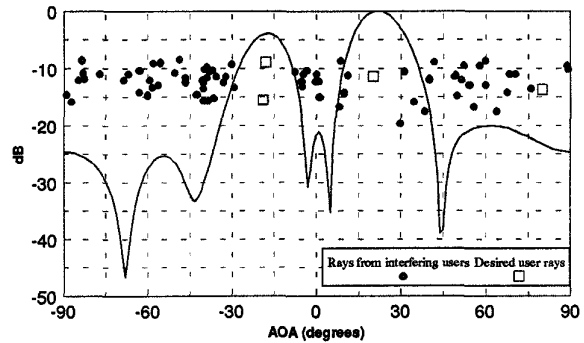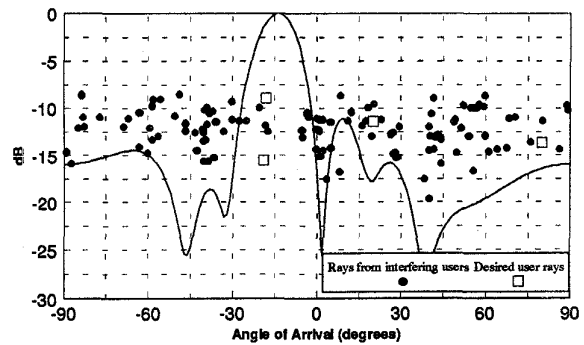TABLE 1: SIMULATION PARAMETERS
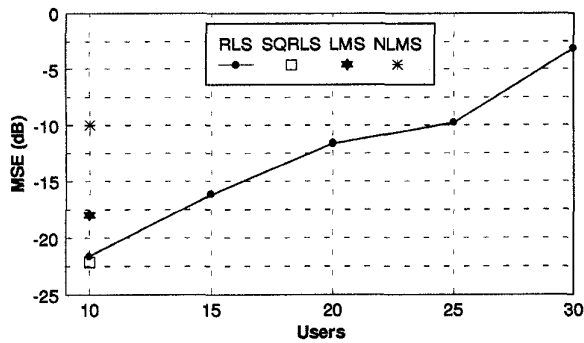
(a)

(b)

Figure 3: a) Mean Square Error and b) Output SIR and Gain for the RLS algorithm, as a function of the system's loading.

(a)

(b)

(c)

Figure 4: Radiation patterns produced for the cases of: a)15 users, b) 20 users, c) 30 users.

In figures 3 and 4, results from the adaptive antenna simulations for a typical microcellular environment and for different adaptive algorithms are presented.

From figure 3a, it can be seen that the RLS and the SQRLS algorithms outperform both the LMS and the NLMS algorithms, which use twice as many samples (1000), as the RLS, SQRLS. From figure 3b, the output SIR values are shown and also what is of most importance, the achieved by the adaptive antenna gain, i.e. the difference between the input and output SIR. It can be seen that although the actual output SIR values can be

947

very small, the gain due to the adaptive antenna, is always substantial, even under very hard situations as that depicted in figure 4(c). There, the interfering rays are overlapping with all the desired rays, but as it can be seen the adaptive antenna manages to produce an output which again offers significant gain.

Furthermore, by examining the graphs of figure 4 in connection with figure 3, the concept of an "intelligent antenna" can be illustrated. Given the spatial distribution of the interfering and the desired signals, the array always attempts to generate the optimum radiation pattern to optimise the output SIR. For example, in figure 4(a), the main beam has been steered towards the second strongest multipath whilst the strongest multipath is only supported by a secondary lobe. This can be compared with figure 4(b) where as the number of interferers increases, the sidelobe level for the second strongest multipath is reduced, and with figure 4(c) where the mainlobe has switched to the strongest desired multipath and no other beams have been formed.

For different simulation scenarios and for different number of users, the above simulations were repeated and from the produced radiation patterns, values for the directivities ranging between 6dB and 9dB, were calculated.

The values calculated for the directivities were then used in the DS-CDMA capacity analysis. The following describes the key parameters for the DS-CDMA system analysed:

- Total number of base-stations: 37, (3 tiers) - Path loss exponent: 4. - Log-normal shadowing std. dev.: 8 dB - Power control: Shadowing and Path loss - Voice activity: 0.5 - Data rate: 8 kbps - E_b / N_0 for BER $\leq 10^{-3}$: 7 dB - Total spreading bandwidth: 1 MHz

These parameters were chosen for the purpose of initial simulations to enable a comparison to be made between an omnidirectional and an adaptive antenna.

In figure 5 the cumulative distribution of the SIRs for the case of 24 users for an omni-directional and for different directivity values, is shown. It is clear from that figure that the SIR improves as the directivity increases. In figure 6 the results from the capacity simulations are presented. It can be seen that the capacity of the DS-CDMA system is substantially increased when an adaptive instead of an omnidirectional antenna, is used at the basestation of a microcell. In order to find an approximate lower bound for the predicted improvement, we considered the worst case of the simulation scenarios, i.e. for the scenario that the adaptive antenna responds with the lowest directivity radiation pattern, (~6dB), it can be seen that the capacity has increased from 21 users/cell/MHz to 102 users/cell/MHz, i.e. almost a five

fold increase has been achieved. It has to be mentioned here that the above figure is clearly a lower bound for the predicted improvement since, one can use the offered by the adaptive antenna gain in SIR to drive the DS-CDMA capacity analysis, which will obviously produce much better results.
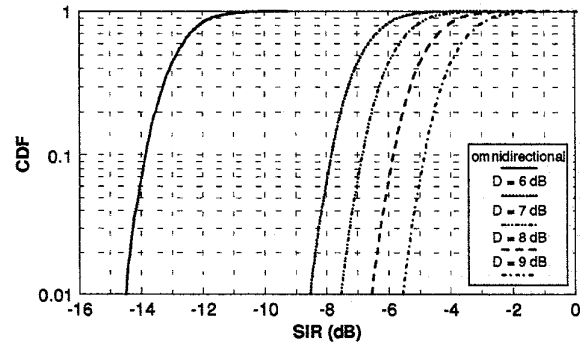

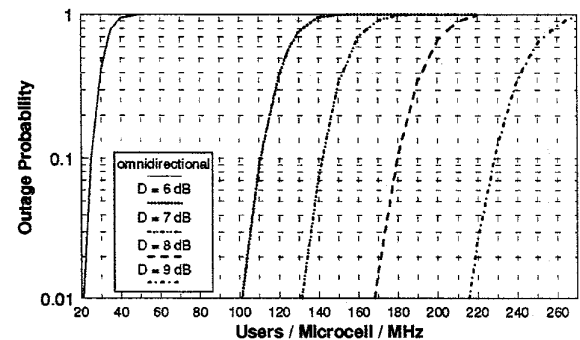Figure 5: Cumulative distribution functions of the SIRs, for 24 users.

Figure 6: Capacity results.

The probability of the distribution of the output SIR for the cases of an omnidirectional and an adaptive antenna with directivity 6 or 8 dB, is depicted in figure 7. The plots are for that number of users/microcell/MHz which corresponds to an outage probability of almost 0.01. It is clear that the distribution of the output SIRs, gets narrower as the directivities of the produced radiation patterns increase. A possible explanation for this effect is that when an adaptive antenna is employed as a basestation antenna, it reduces the area from where it receives interfering signals, through the directivity of its produced radiation pattern. This reduction in the distribution of the SIR is a very important improvement because it means that the power control mechanism can now operate over a much smaller dynamic range, which greatly reduces the possibility for power control inaccuracies, to which the DS-CDMA system is extremely susceptible.
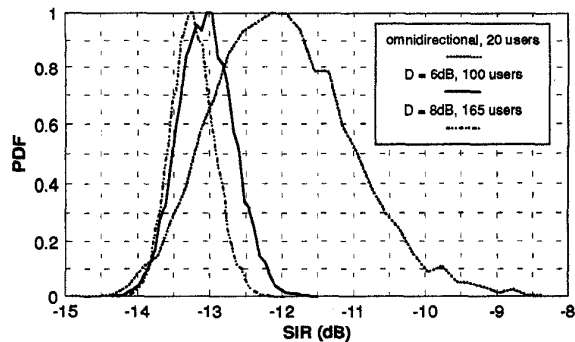
948

Figure 7: Probability distribution function for the output SIRs with an omnidirectional and an adaptive antenna.

IV. CONCLUSIONS

A new ray based simulation model for an adaptive antenna in a DS-CDMA system was presented. Results for a typical microcellular environment highlighted the behaviour of an adaptive antenna when used in conjunction with DS-CDMA and showed that substantial gain in terms of output SIR can be achieved even in very hard situations. DS-CDMA capacity analysis for the scenarios considered showed a minimum of five fold increase in the overall spectrum efficiency. Finally, it was shown that less restrictive conditions for the critical for DS-CDMA power control mechanism can be achieved with an adaptive antenna.

ACKNOWLEDGEMENTS

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