Performance Enhancement of DS-CDMA Microcellular Networks with Adaptive Antennas

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Abstract: This paper considers the performance of a DS-CDMA system which employs adaptive antenna technology at the basestation site of a microcell. 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 Monte-Carlo type DS-CDMA capacity analysis, the potential performance enhancement and the sensitivity of the system upon the misspointing of the main beam, are evaluated.

I. Introduction

The increasing demand for spectrum efficient mobile communications systems motivates the need for new techniques in order to improve spectrum utilisation, [1-2]. Proposals include the deployment of smaller cells, combination of different cell types in a mixed cell architecture, fixed sector or multibeam antennas, as well as spatial processing with adaptive (or smart) antenna arrays at base station sites. With efficient use of spatial processing at a cell site, optimum receive and transmit beams can be used to improve the system's performance in terms of the available capacity and quality of service parameters [3-11]. This approach is usually referred to as SDMA (Space Division Multiple Access SDMA), and enables multiple users within the same cell to be accommodated on the same frequency and time slot by exploiting the spatial filtering properties offered by the adaptive antenna.

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.

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

II. Adaptive Antennas and Angle of Arrival

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 steer a beam towards some direction (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. However, since in large cells the mobiles usually travel with speeds, the time available for the chosen algorithm to converge, is critically limited.

The direction finding approach in a microcellular environment there is no adaptation problem but since most of the multipath signals in a microcellular narrowband DS-CDMA system are coherent, unless additional techniques which complicate even further the problem and are not always stable, are considered, performance degradation will occur, [12].

All the above indicate that in a harsh environment like the environment for mobile communications, the choice of the best approach for an adaptive antenna is a complicated issue to resolve. Different environments have different propagation characteristics which suit different approaches.

III. SIMULATION MODEL

The developed 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 3D ray- tracing simulation tool that was developed at the University of Bristol, [13]. The input parameters to this tool include geographical data bases of the service areas, the number of reflections, transmissions and diffractions, the transmitted power, 3D antenna radiation patterns etc. The output file includes the electric field, the time delay and the angle of arrival.

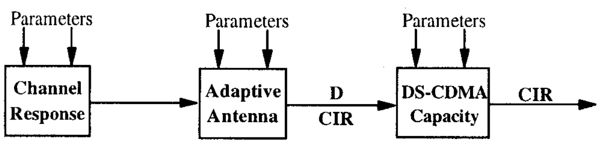


Figure 1: Simulation model block diagram

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.

$x_n(k)$ 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:

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

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

$\mathbf{r}_m(k) = \mathbf{d}_m(k) \cdot \mathbf{PN}_m(k) \cdot e^{j\xi_m}$, 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 signal-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. The probability of the distribution of the output SIR for the case of an omnidirectional antenna is depicted in figure 2.

The total interference seen by the central basestation due to both the in-cell and the out-of-cell interferers, is:

$$I_{tot} = \int_0^{(2Tiers+1)R_{mic}} \int_0^{2\pi} \frac{P(l,\varphi)}{\pi R_{mic}^2} D(\varphi) rl\,dl\,d\varphi = \frac{I}{D}$$

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.

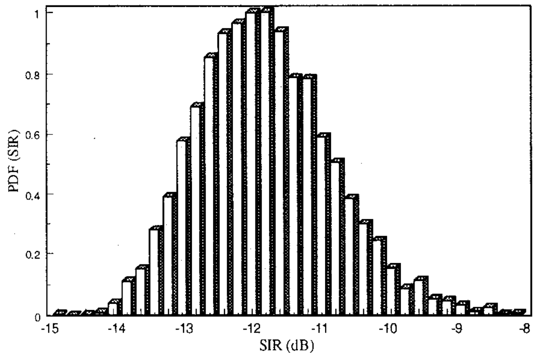


Figure 2: Probability distribution function for the output SIRs with an omnidirectional antenna.

3. Results

The model for the adaptive antenna offers the capability of selecting one from several adaptive processing algorithms. In [6-8] different algorithms were compared and the superiority of the RLS algorithms was proved. Here the RLS algorithm is considered, [16]:

$$\mathbf{w}(k+1)=\mathbf{w}(k)+\frac{\mathbf{R}^{-1}(k)\cdot\mathbf{x}^{*}(k+1)}{\alpha+\mathbf{x}^{T}(k+1)\cdot\mathbf{R}^{-1}(k)\cdot\mathbf{x}^{*}(k+1)}\cdot e(k+1)$$

$$\mathbf{R}^{-1}(k+1)=\frac{1}{\alpha}\left[\mathbf{R}^{-1}(k)-\frac{\mathbf{R}^{-1}(k)\cdot\mathbf{x}^{*}(k+1)\cdot\mathbf{x}^{T}(k+1)\cdot\mathbf{R}^{-1}(k)}{\alpha+\mathbf{x}^{T}(k+1)\cdot\mathbf{R}^{-1}(k)\cdot\mathbf{x}^{*}(k+1)}\right]$$

$$\mathbf{R}^{-1}(0)=\delta^{-1}\cdot\mathbf{I},$$

where d is a small positive constant and the value for the *forgetting factor* a is very dependent on the fading rate of the channel with the best value close to 1, [15].

Table 1 summarises the parameters used in the simulations. In addition, each user in the simulation is stationary and power controlled by the base station.

Runs	10
Samples	500
Array elements	8
Interelement spacing	$\lambda/2$
Algorithm	RLS
Forgetting Factor	1

Table 1: Adaptive Antenna Simulation Parameters

In figure 3 an example of a 3D impulse response of the radio channel for a NLOS case is shown.

Figure 4 shows a compass plot for the calculated from the RLS algorithm final complex weights for each antenna array element, for the case of 20 users. The horizontal axis is the angle and the vertical axis is proportional to the magnitude of each vector.

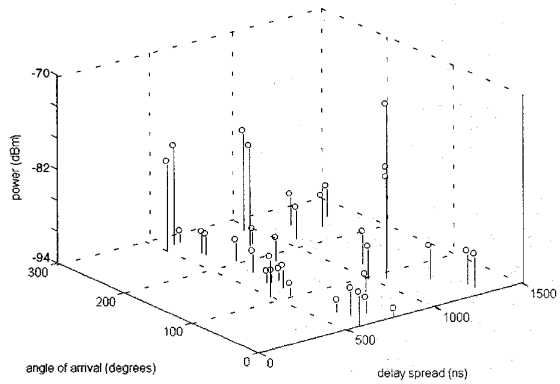


Figure 3: An example of a NLOS 3D Impulse response.

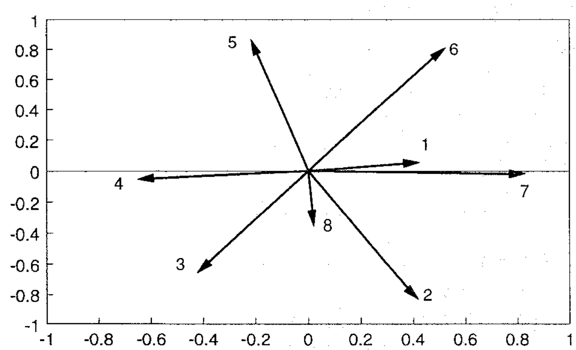


Figure 4: The final weight vectors for each antenna element calculated from the RLS algorithm for the case of 20 users.

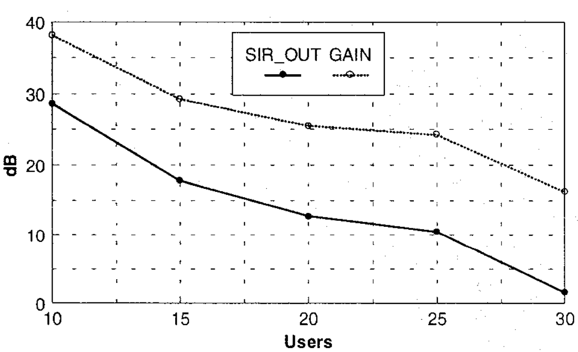
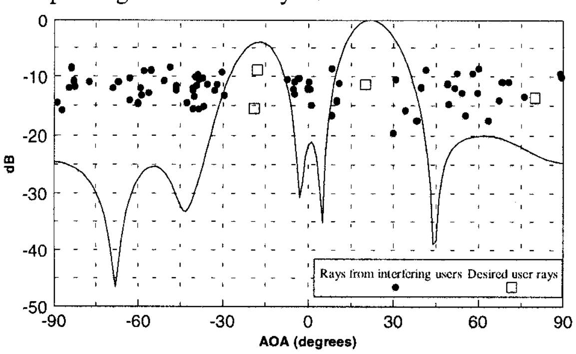


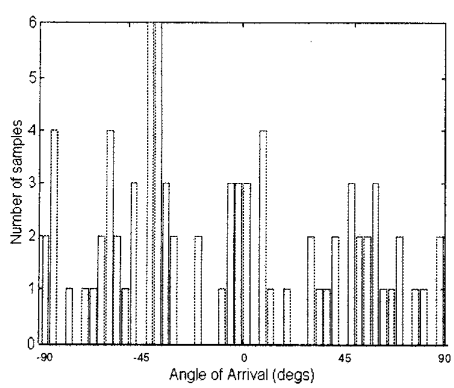
Figure 5: Output SIR and Gain for the RLS algorithm, as a function of the system's loading.

In figure 5 the output SIR values and also what is of great importance, the achieved by the adaptive antenna gain, i.e. the difference between the input and output SIR, are shown. It can be seen that although the actual output SIR values can be very small, the gain due to the adaptive antenna, is always substantial, even under very difficult multipath conditions.

Furthermore, by examining figure 6a in connection with figure 5, the concept of a "smart antenna" can be illustrated. Given the spatial distribution of the interfering and the desired signals, the adaptive antenna always attempts to generate the optimum radiation pattern which corresponds to the optimum output SIR. As a result of that concept, in figure 6a the adaptive antenna has steered its main beam towards the second strongest multipath whilst the strongest multipath is only supported by a secondary lobe. The distribution of the arriving at the base station multipath signals, is shown in figure 6b. There it can be seen that due to the lower height of the BS antenna and the close proximity of the scattering objects in a microcellular environment, the angular spread of the multipath signals can be very wide.



(a)



(b)

Figure 6: a): Radiation patterns produced for the case of 20 users. b): The distribution of the Angles of Arrival for the scenario considered in a).

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, as shown in figure 7.

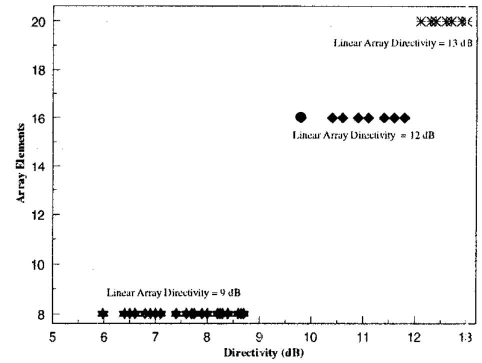


Figure 7: Directivity values calculated from different simulations.

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.

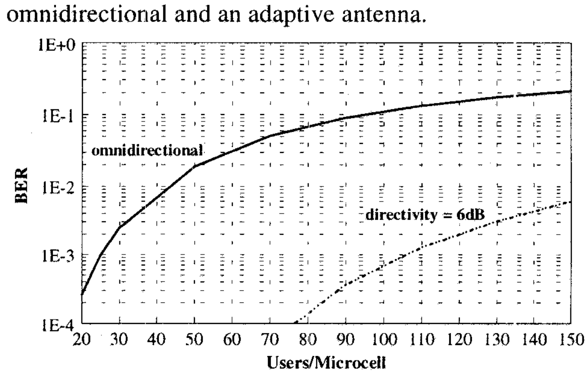


Figure 8: Capacity results.

The BER is calculated from the formula, [16]: $P_b \approx Q\left(\sqrt{3SF * CIR}\right)$, with $Q(z)$ the standard Q-function and SF the spreading factor. This equation is accurate for perfect power control and for large number of users. In figure 8 the average BER for each loading case is considered. In figure 7 the results from the capacity simulations are presented. 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 ~24 users/cell/MHz to 108 users/cell/MHz ($BER = 10^{-3}$), i.e. almost a five fold increase has been achieved when an adaptive instead of an omnidirectional antenna, is used at the basestation of a microcell.

From the simulations it was noticed that there may be a slight misspointing of the main beam. In order to investigate how this affects the achieved capacity, the results shown in figure 9 were produced. Due to the misspointing effect the desired user's signal will be attenuated and as a result the overall SIR will be reduced. From figure 9 can be seen that the capacity is substantially reduced for more than 2 degrees of main beam misspointing.

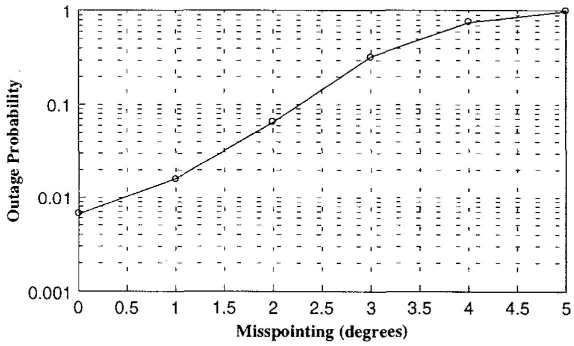


Figure 9: The effect of main beam misspointing on the achieved capacity.

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 difficult multipath 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 the achieved capacity is sensitive to the misspointing effect.

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