7 CDMA DOWNLINK ANALYSIS WITH COMBINED BEAMFORMING ARRAYS

7.1 INTRODUCTION

In chapter 4 corner cell distributed adaptive arrays with combined beamforming of the sub-arrays were compared analytically to independent optimum beamforming of the arrays. It was shown that a higher SINR can be achieved with combined optimum beamforming of all the sub-array signals compared to forming individual optimum beams for each sub-array together with optimum combining of the individual sub-array output signals.

In chapter 1 it was shown that corner cell distributed adaptive arrays with combined beamforming of the sub-arrays can support multiple co-channel interferes in the same cell as the desired user for time division access systems (TDMA) at a lower outage probability than arrays with individual optimum beamforming. The effect of angular spread on the performance of the arrays was also investigated.

A mobile moving between cells in TDMA systems will be given a hard handoff to the cell with the strongest signal[47]. In CDMA systems all users in the network operate on the same frequency channel, but are separated from each other by orthogonal time codes. There is more than one frequency in a CDMA network, but a new frequency will only be used if the capacity of the network on the first frequency is at its maximum. A hard handoff between different frequencies in CDMA is possible, but only in the case where the systems can support it and when the one frequency cannot accept any more calls. In the analysis to follow, handoff to other frequencies is not considered for CDMA systems.

A CDMA mobile constantly monitors the pilots[48] of all cells with a neighbor list supplied to the mobile by the base station. If the signal of one or more base stations is above a certain threshold, the mobile will go into soft handoff with those cells. All base stations

[47] A hard handoff in TDMA systems means that the mobile will retune its receiver to a different frequency channel as directed by the base station handling the call.
[48] Constant power signal transmitted by each base station sector on Walsh code 0, with a unique PN offset for each sector and BTS.

that are in soft/softer handoff[49] with the mobile will transmit equal power (minimum power required to overcome slow fading between mobile and all BTSs in soft handoff) signals to the mobile. The mobile in handoff will then combine all the downlink signals with maximum ratio combining, improving the signal to noise ratio at the mobile compared to the no-handoff case. A mobile experiencing a fade from one of the base stations will most probably not experience a simultaneous fade from the other base stations. This is due to the fact that the base stations are located far apart and therefore the slow fading between BTSs and mobile will be uncorrelated. This gives a diversity gain, called macroscopic diversity [35], allowing the base stations to transmit lower power for a certain signal to noise ratio at the mobile.

In this chapter, it will be investigated whether there is a benefit for the CDMA downlink in combined optimum beamforming of the arrays in soft handoff relative to independent array beamforming of the arrays. The performance will be investigated in terms of the signal to noise ratio as well as outage probability. The basic concept is that the arrays in soft handoff will transmit a reduced signal to the mobiles that are interfered with, since the weights are formed by "looking" at the mobiles from different directions at the same time (see Figure 78). It will be investigated whether this will result in an increase in the overall signal to noise ratio of the mobiles being interfered with when transmitting to a specific mobile.

[49] Term used in CDMA describing mobiles connected to multiple sectors or base stations.

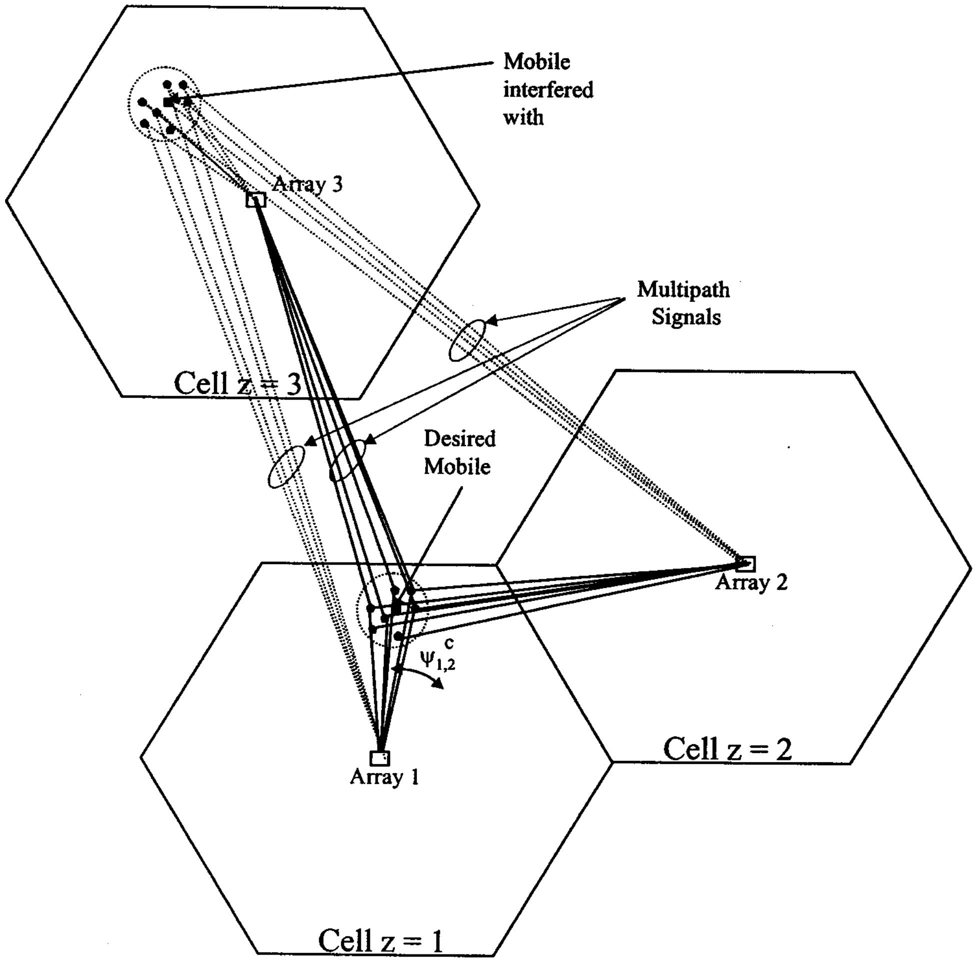

Figure 78: Mobile in soft handoff with three adaptive arrays, showing multipath signals to the desired mobile (solid lines) from the base stations as well as to a mobile being interferer with (dashed lines).

The geometry will be described first in this chapter. This will be followed by formulating the beamforming weight vectors for individual and combined optimum beamforming. The formulation also includes the application of the weight vectors to determine the signal to noise ratio at all the mobiles. This is followed by estimating the SINR of combined and individual beamforming for a three cell network having four mobiles, each in two way handoff, with fixed mobile locations and without fading. Next, the received signal is determined for a seven cell network for both independent and combined beamforming for a mobile in two way soft handoff in a fading environment. This is followed by simulation results for a single iteration as well as outage probability estimation with a Monte-Carlo procedure. Finally, conclusions will be drawn on the performance of independent vs. combined optimum beamforming of the arrays in soft handoff for the CDMA downlink.

7.1 Geometry

It is assumed that the base stations with sectorized or antenna arrays are located at the center of the hexagonal cells[50]. Each base station consists of three 120° sectorized antennas or arrays with a 120° element pattern. The boresight of array in sector 1 is 60°, array in sector 2 is 180° and array in sector 3 is 300° and the radius of each cell is R. The sectors are numbered as shown in Figure 79. The angle relative to the array boresight is ψ and the angle between array (located in cell z_d) boresight and mobile d is $\psi_{z_d,d}$.

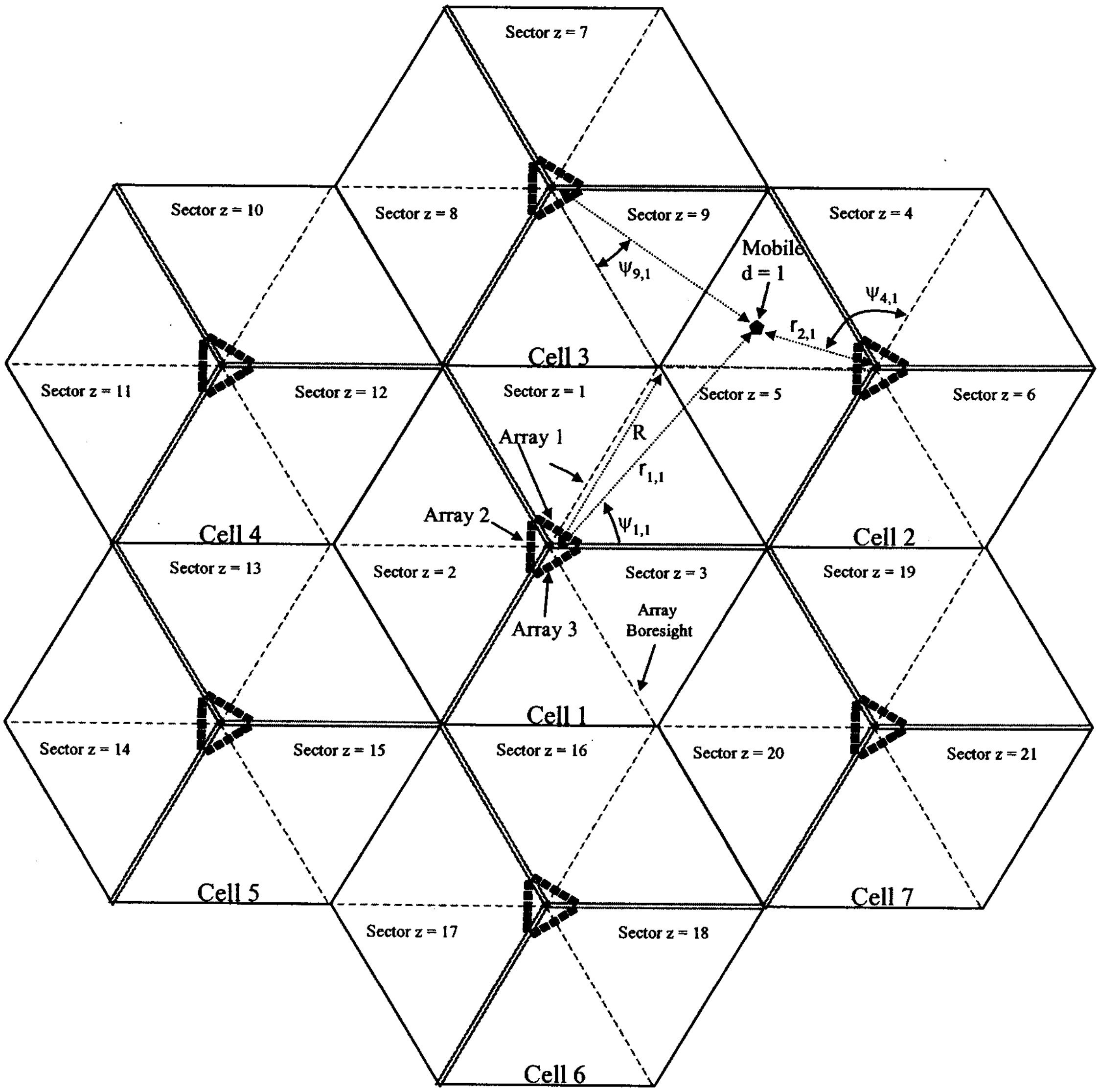

Figure 79: CDMA adaptive array network geometry.

[50] Distributed arrays in the CDMA downlink are located at the cell center, compared to the corner of the cell in the TDMA systems investigated earlier.

7.2 Downlink Formulation

Using the formulation in [30], the received signal $x_{d_{des}}$ at the desired mobile with independent array beamforming is:

$$
\begin{aligned}
x_{d_{des}}(t) = & \sum_{z_{d_{des}}=1}^{Z_{d_{des}}} \Big(\sqrt{P_{d_{des}} G_{z_{d_{des}},d_{des}}}\; b_{d_{des}}(t-\tau_{z_{d_{des}},d_{des}})\; c_{d_{des}}(t-\tau_{z_{d_{des}},d_{des}}) \\
& \quad \mathbf{W}^{H}_{z_{d_{des}},d_{des}} \mathbf{U}_{z_{d_{des}},d_{des}} \Big) \\
& + \sum_{\substack{d_{ic}=1 \\ d_{ic}\neq d_{des}}}^{D} \sum_{z_{d_{ic}}} \Big(\vartheta_{d_{ic}} \sqrt{P_{d_{ic}} G_{z_{d_{ic}},d_{ic}}}\; b_{d_{ic}}(t-\tau_{z_{d_{ic}},d_{ic}})\; c_{d_{ic}}(t-\tau_{z_{d_{ic}},d_{ic}}) \\
& \quad \mathbf{W}^{H}_{z_{d_{ic}},d_{ic}} \mathbf{U}_{z_{ic},d_{ic}} \Big) \qquad (192) \\
& + \sum_{d_{oc}=1}^{D} \sum_{z_{d_{oc}}} \Big(\vartheta_{d_{oc}} \sqrt{P_{d_{oc}} G_{z_{d_{oc}},d_{oc}}}\; b_{d_{oc}}(t-\tau_{z_{d_{oc}},d_{oc}})\; c_{d_{oc}}(t-\tau_{z_{d_{oc}},d_{oc}}) \\
& \quad \mathbf{W}^{H}_{z_{d_{oc}},d_{oc}} \mathbf{U}_{z_{d_{oc}},d_{oc}} \Big) \\
& + n_{d_{des}}(t)
\end{aligned}
$$

and with combined beamforming is (modification of [30]):

$$
\begin{aligned}
\ddot{x}_{d_{des}}(t) = & \sum_{z_{d_{des}}=1}^{Z_{d_{des}}} \Big(\sqrt{P_{d_{des}} \ddot{G}_{(\cap z_{d_{des}}),d_{des}}}\; b_{d_{des}}(t-\ddot{\tau}_{(\cap z_{d_{des}}),d_{des}})\; \ddot{c}_{d_{des}}(t-\ddot{\tau}_{(\cap z_{d_{des}}),d_{des}}) \\
& \quad \dddot{\mathbf{W}}^{H}_{(\cap z_{d_{des}}),d_{des}} \ddot{\mathbf{U}}_{(\cap z_{d_{des}}),d_{des}} \Big) \\
& + \sum_{\substack{d_{ic}=1 \\ d_{ic}\neq d_{des}}}^{D} \Big(\vartheta_{d_{ic}} \sqrt{P_{d_{ic}} \ddot{G}_{(\cap z_{d_{ic}}),d_{ic}}}\; b_{d_{ic}}(t-\ddot{\tau}_{(\cap z_{d_{ic}}),d_{ic}})\; c_{d_{ic}}(t-\ddot{\tau}_{(\cap z_{d_{ic}}),d_{ic}}) \\
& \quad \dddot{\mathbf{W}}^{H}_{(\cap z_{d_{ic}}),d_{ic}} \ddot{\mathbf{U}}_{(\cap z_{ic}),d_{ic}} \Big) \\
& + \sum_{d_{oc}=1}^{D} \Big(\vartheta_{d_{oc}} \sqrt{P_{d_{oc}} \ddot{G}_{(\cap z_{d_{oc}}),d_{oc}}}\; b_{d_{oc}}(t-\ddot{\tau}_{(\cap z_{d_{oc}}),d_{oc}})\; c_{d_{oc}}(t-\ddot{\tau}_{(\cap z_{d_{oc}}),d_{oc}}) \\
& \quad \dddot{\mathbf{W}}^{H}_{(\cap z_{d_{oc}}),d_{oc}} \ddot{\mathbf{U}}_{(\cap z_{oc}),d_{oc}} \Big) \\
& + n_{d_{des}}(t)
\end{aligned}
$$

(193)

where

d_{des} is the desired mobile number,

d_{ic} is the d^{th} mobile in the same sector as the desired mobile,

$Z_{d_{des}}$ is the number of sectors in handoff with the desired mobile,

z_d is the sector number in handoff with mobile d,

$z_{d_{des}}$ is the sector number in handoff with the desired mobile,

$z_{d_{oc}}$ is the handoff sector number of the d^{th} mobile in a sector not containing the desired mobile,

$\bigcap z_d$ is the combination of sectors that the d^{th} mobile is in handoff with,

D is the number of mobiles per sector,

$\vartheta_{d_{ic}}$ is the voice activity factor of mobile d_{ic},

$P_{d_{des}}$ is the desired signal power transmitted from the base stations in handoff,

P_d is the power transmitted from the base station to the d^{th} mobile,

$G_{z_{d_{des}},d_{des}}$ is the path gain between sector $z_{d_{des}}$ and mobile d_{des},

$\dddot{G}_{z_{d_{des}},d_{des}}$ is the combined BF path gain between the sectors $(\bigcap z_{d_q})$ and the mobile d_{des},

$G_{z_d,d}$ is the path gain between sector z_d and mobile d,

$\dddot{G}_{(\bigcap z_d),d}$ is the combined BF path gain between sectors $(\bigcap z_d)$ and mobile d,

b_d is the data bits of mobile d,

c_d is the spreading code of mobile d,

$\tau_{z_d,d}$ is the propagation delay for signals between sector z_d and mobile d,

$\dddot{\tau}_{(\bigcap z_d),d}$ is the combined BF propagation delay for arrays $(\bigcap z_d)$ in handoff with mobile d,

$\mathbf{W}_{z_d,d}$ is the independent array BF weight vector from sector z_d and mobile d,

$\dddot{\mathbf{W}}_{(\bigcap z_d),d}$ is the combined array BF weight vector for arrays $(\bigcap z_d)$ in handoff with mobile d,

$\mathbf{U}_{z_d,d}$ is the array vector in sector z_d transmitting to mobile d,

$\dddot{\mathbf{U}}_{(\cap z_d),d}$ is the combined beamforming array vector for arrays $(\cap z_d)$ in handoff with mobile d,

$n_{d_{des}}$ is the noise power at the desired mobile,

$(\,)^H$ is the complex conjugate transpose.

The received signal at the mobile is now despread with the Walsh code of the desired signal. In the absence of multipath, Walsh codes has the property that signals multiplied by different Walsh codes results in uncorrelated signals in the same sector (where they are completely synchronized) [50]. Multipath causes some correlation between the Walsh codes and thereby increasing the interference to the desired signal from the other users in the same sector. In the simulations to follow, it will be assumed that the Walsh codes remain uncorrelated in the presence of multipath.

After despreading, a RAKE receiver is used at the mobile. The rake receiver will track L multipath signal components separated by multiples of the chip period[51]. The L multipath signal components (called fingers in CDMA) are then coherently combined[52]. A mobile that is in soft handoff with multiple sectors, will receive the same information from all these sectors. The RAKE receiver will search for the L strongest multipath signals from all the sectors in handoff and coherently combine them. The desired component of the received signal (after the RAKE receiver) at the desired mobile with independent array beamforming is:

$$x_{d_{des}}^{des}(t) = g_p\sqrt{P_{d_{des}}}\sum_{\ell=1}^{L}\left|\sqrt{G_{d_{des}}(\ell)}\, b_{d_{des}}\left[t-\tau_{d_{des}}(\ell)\right]\mathbf{W}_{d_{des}}^{H}(\ell)\mathbf{U}_{d_{des}}(\ell)\right| \tag{194}$$

where g_p is the processing gain and for each multipath component ℓ, $\sqrt{G_{d_{des}}(\ell)}$ is the path gain, $\tau_{d_{des}}(\ell)$ is the delay, $\mathbf{W}_{d_{des}}^{H}(\ell)$ is the weight vector and $\mathbf{U}_{d_{des}}(\ell)$ is the array vector. Without loss of generality, it is assumed that the delays $\tau_{d_{des}}(\ell) = 0$. Equation (194) then becomes:

---

[51] Walsh codes are spreading codes, and each spreading code bit is called a chip in CDMA.
[52] Added together in phase.

$$x_{d_{des}}^{des}(t) = g_p \sqrt{P_{d_{des}}} \sum_{\ell=1}^{L} \left| \sqrt{G_{d_{des}}(\ell)}\, b_{d_{des}}(t)\ \mathbf{W}_{d_{des}}^{H}(\ell) \mathbf{U}_{d_{des}}(\ell) \right| \tag{195}$$

The desired component of the received signal at the desired mobile with combined beamforming is:

$$\dddot{x}_{d_{des}}^{des}(t) = g_p \sqrt{P_{d_{des}}} \sum_{\ell=1}^{L} \left| \sqrt{\ddot{G}_{d_{des}}(\ell)}\, b_{d_{des}}(t)\, \dddot{\mathbf{W}}_{d_{des}}^{H}(\ell)\ \ddot{\mathbf{U}}_{d_{des}}(\ell) \right| \tag{196}$$

The background noise is generally well below the total power received by the mobile and may therefore be ignored [30]. The interference component of the received signal at the desired mobile with independent array beamforming is:

$$x_{d_{des}}^{int} = \sum_{d_{oc}=1}^{D} \sum_{z_{d_{oc}}} \vartheta_{d_{oc}} \sqrt{P_{d_{oc}}\, G_{z_{d_{oc}},d_{q_{oc}}}}\ \mathbf{W}_{z_{d_{oc}},d_{oc}}^{H}\ \mathbf{U}_{z_{oc},d_{oc}} \tag{197}$$

and with combined array beamforming:

$$\dddot{x}_{d_{des}}^{int} = \sum_{d_{oc}=1}^{D} \vartheta_{d_{oc}} \sqrt{P_{d_{oc}}\, \ddot{G}_{(\cap z_{d_{oc}}),d_{oc}}}\ \dddot{\mathbf{W}}_{(\cap z_{d_{oc}}),\, d_{oc}}^{H}\ \ddot{\mathbf{U}}_{(\cap z_{d_{oc}}),d_{oc}} \tag{198}$$

Individual array beamforming weights can be determined with the feedback method from each array in soft handoff separately (see section 7.4). Combined array weights can be determined with the feedback method from all arrays in soft handoff as one large array. The weights of the combined arrays in handoff will be adapted such that the signals from all three base station arrays will add coherently at the mobile. The RAKE fingers are then determined from the multipath signals (separated by more than one chip period) arriving at the mobile from the combined array.

The ℓ^{th} component of the weight vector for the individual array beamforming $\mathbf{W}_{z_d,d}$ (determined with the feedback method as described in section 7.4) is given by:

$$\mathbf{W}_{z_d,d}(\ell) = \frac{M\mathbf{R}_{z_d}^{-1}(\ell)\mathbf{U}_d(\ell)}{\mathbf{U}_d^{T}(\ell)\ \mathbf{R}_{z_d}^{-1}(\ell)\mathbf{U}_d(\ell)} \tag{199}$$

where $\mathbf{R}_{z_d}^{-1}(\ell)$ is the inverse of the co-variance matrix for each individual array z_d in handoff to the mobile d, and $\mathbf{U}_d(\ell)$ is the array vector towards the signal d for the ℓ^{th}

multipath component. The array is multiplied by the number of elements, in order to compare it to the sectorized case, i.e. the array gain is not part of the normalization. The array vector of signal d for the ℓ^{th} multipath component is:

$$\mathbf{U}_d(\ell) = 1, e^{j\pi \sin\psi_{z_d,d}(\ell)}, e^{j2\pi \sin\psi_{z_d,d}(\ell)}, \ldots, e^{j(M-1)\pi \sin\psi^c_{z_d,d}(\ell)} \tag{200}$$

The ℓ^{th} component of the weight vector for the combined array $\dddot{\mathbf{W}}^H_{(\cap z_d),d}$ that mobile d is in handoff with is:

$$\dddot{\mathbf{W}}^H_{(\cap z_d),d}(\ell) = \frac{M N_{z_d} \dddot{\mathbf{R}}^{-1}_{(\cap z_d)}(\ell)\, \dddot{\mathbf{U}}_d(\ell)}{\dddot{\mathbf{U}}^T_d(\ell) \dddot{\mathbf{R}}^{-1}_{(\cap z_d)}(\ell) \dddot{\mathbf{U}}_d(\ell)} \tag{201}$$

where $\dddot{\mathbf{R}}^{-1}_{(\cap z_d)}$ is the inverse of the co-variance matrix of the combined arrays $(\cap z_d)$ in soft handoff with the mobile. The array weight contains the array gain relative to the sector antenna, where N_{z_d} is the number of arrays in handoff with mobile. The covariance matrix for independent array beamforming is:

$$\mathbf{R}_{z_d,d} = E\left[\mathbf{X}_{z_d}\ \mathbf{X}^H_{z_d}\right] \tag{202}$$

where $\mathbf{X}_{z_d}$ are the signals at elements of array z_d, given by:

$$\mathbf{X}_{z_d}(t) = \sum_{\substack{d=1 \\ d \neq d_{des}}}^{D} \sqrt{G_{z_d}} \left\{b_d(t)\, c_d(t)\right\} \left[1, e^{j\pi \sin\psi^c_{z_d,d}}, e^{j2\pi \sin\psi^c_{z_d,d}}, \ldots, e^{j(M-1)\pi \sin\psi^c_{z_d,d}}\right] + \mathbf{n}_{z_d} \tag{203}$$

Inserting (203) in (202) and using the fact that the spreading codes of the mobiles are orthogonal over a certain time period, the covariance matrix can be written as (see Appendix A):

$$\mathbf{R}_{z_d,d} = \sum_{\substack{d=1 \\ d \neq d_{des}}}^{D} \left[\sqrt{G_{z_d}} \left\{\mathbf{U}_d\ \mathbf{U}^H_d\right\}\right] + \sigma^2_N\, \mathbf{I} \tag{204}$$

where σ^2_N is the noise power at the array elements and $\mathbf{I}$ is the unity vector. The covariance matrix for combined array beamforming is:

$$\ddot{\mathbf{R}}_{(\cap z_d),d} = E\left[\ddot{\mathbf{X}}_{z_d}\ \ddot{\mathbf{X}}^H_{z_d}\right] \tag{205}$$

where $\ddot{\mathbf{X}}_{(\cap z_d)}$ are the signals at elements of the combined array $\cap z_d$, given by:

$$\ddot{\mathbf{X}}_{(\cap z_d)}(t) = \sum_{\substack{d=1 \\ d \neq d_{des}}}^{D} \sqrt{G_{(\cap z_d),d}}\,\{b_d(t)\ c_d(t)\}\,[1,\ e^{j\pi \sin\psi^c_{z_d,d}},\ e^{j2\pi \sin\psi^c_{z_d,d}},\ldots,$$

$$e^{j(M-1)\pi \sin\psi^c_{z_d,d}},\ 1,\ e^{j\pi \sin\psi^c_{z_d,d}},\ e^{j2\pi \sin\psi^c_{z_d,d}},\ldots,\ e^{j(M-1)\pi \sin\psi^c_{z_d,d}},\ldots] \tag{206}$$

$$+\ \mathbf{n}_d$$

which can be written as:

$$\ddot{\mathbf{X}}_{(\cap z_d)}(t) = \sum_{\substack{d=1 \\ d \neq d_{des}}}^{D} \left[\sqrt{G_{(\cap z_d),d}}\,\{b_d(t)\ c_d(t)\}\,\ddot{\mathbf{U}}_{(\cap z_d)}\right] + \mathbf{n}_d \tag{207}$$

where $\mathbf{U}_{(\cap z_d)}$ is the concatenated vector of all the array vectors $\cap z_d$ that are in soft handoff with the mobile d. Inserting (207) in (205), and using the fact that the spreading codes (Walsh codes) of the mobiles are orthogonal over a certain time period, the covariance matrix for combined beamforming can be written as (see Appendix B):

$$\ddot{\mathbf{R}}_{(\cap z_d),d} = \sum_{\substack{d=1 \\ d \neq d_{des}}}^{D} \left[G_{(\cap z_d),d}\left\{\ddot{\mathbf{U}}_{z_d}\ \ddot{\mathbf{U}}^H_{z_d}\right\}\right] + \sigma_N^2\ \mathbf{I} \tag{208}$$

7.3 Power Control of Mobiles

A signal transmitted to mobile d will interfere with all other mobiles located within the angular bounds of the sector in handoff with mobile d. This will reduce the signal to noise ratio of the mobiles interfered by the signal of mobile d. On the other hand, signals are also transmitted at the same time to other mobiles from other sectors, thereby interfering with mobile d and reducing its signal to noise ratio. In order to maintain adequate SINR at all mobile, tight power control is required in a CDMA network.

Power control as implemented in this thesis is based on an iterative procedure. Initially the power for all mobiles is equalized. The mobile with the worst signal to noise ratio is then determined (say mobile d_5). The mobiles interfering with the mobile d_5 is then sorted in terms of interference power received at mobile d_5. The power of the strongest interferer (say mobile d_8) is then reduced by a certain fixed amount only if the SINR of the interfering mobile d_8 after this power adjustment is above the desired SINR threshold. The power of the other interfering mobiles is then reduced in turn only if the SINR of the mobiles after power adjustment is above the desired SINR threshold. After the power of all the mobiles interfering with d_5 has been appropriately adjusted, the SINRs of all the mobiles are determined using the newly calculated power. The mobile with the lowest SINR is again determined and the power adjustment procedure for all the mobiles interfering with this mobile is repeated. The procedure is repeated a number of times until the SINR of all mobiles are above the threshold or the maximum number of iterations has been reached. If the maximum number of iterations has been reached, it normally means that the power of the interferers can no longer be adjusted without reducing the SINR of the interferers below the SINR threshold. In this case, some mobiles may have a SINR that is below the required SINR, resulting in an outage

7.4 Downlink Propagation Channel Array Signal Matrix Estimation

In order to transmit a maximum signal from the base station to the desired mobile while minimizing the interference to the other mobiles, the downlink propagation channel array signal matrix is required. The channel signal vector of array z to mobile d is $\mathbf{X}_{z_d}$. The complex channel signal matrix of array z is the assembly of all the channel vectors for all the mobiles, given by:

$$\mathbf{X}_z = \{\mathbf{X}_{z_1}, \mathbf{X}_{z_2}, \ldots\ldots, \mathbf{X}_{z_D}\} \quad (209)$$

The downlink propagation channel array signal matrix cannot be determined from the uplink information, as the uplink and downlink are not reciprocal (scattering behavior is different) due to a relatively large duplex frequency separation[53] [30].

In [14] a method is presented whereby the complex array signal matrix can be measured, providing a complete response to all reflections and scattering in the propagation channel between the base station array and the mobile. The downlink channel signal matrix is measured using feedback from the mobiles. There are two modes of operation. The regular data mode and the probing mode. During the probing mode, the regular data information to the mobile is temporarily halted while the propagation channel is measured. Each element of the array is excited in turn with a probing signal, agreed on by the transmitter and the mobiles. Each mobile measures the relative amplitude and phase response of the probing signals. The probing signals are orthogonal to each other (signals can be separated in time or transmitted together on different orthogonal codes), so that each probing signal channel response can be measured independently by the mobiles. After measuring the complex channel response at each mobile, the measurements are fed back to the base station on the reverse channel. The channel response matrix can then be used during the regular data mode to transmit to the mobiles. This method requires a large amount of information to be transmitted by the mobile back to the base station on the reverse channel.

An alternative approach, minimizing the feedback data on the reverse link, is presented in [44]. This method is well suited to CDMA systems. The received signal at time sample $i \in \{1,2,\ldots,\infty\}$ at each mobile is correlated with its own Walsh code to obtain signal $v_d(i)$, $d=\{1,2,..,D\}$. Nonlinear processing is applied to $v_d(i)$ to extract the hard limited (+ 1 and –1) transmitted information bits $b_d(i)$. A scalar error between $v_d(i)$ and $b_d(i)$ is then determined. If this error is above a certain threshold value, it will be fed back to the BTS, in order to minimize the error signal information traffic. The base station will then recursively update its adaptive array transmit weight matrix, and thereby achieve the optimum downlink signal to noise ratio at each mobile. Various recursive update methods can be used, such as the least squared or BEACON method proposed in [44]. The propagation channel vector for each mobile at the minimum error is then proportional to the conjugate of the weight vector. Another very important advantage of this method is that the transmit weight matrix is updated while the downlink data is being transmitted, thereby not disturbing the live mobile traffic.

The above methods require that the propagation channel is slow varying with respect to the data rate, i.e. the fading rate is much lower than the data rate. This is applicable to narrowband CDMA systems. It should be noted here that existing mobiles does not contain the functionality to determine the error and transmit it back to the base station. This may be

[53] 60 MHz for 1900 MHz North American cellular systems.

incorporated in a special or dedicated error feedback channel (i.e., Walsh code) required on the reverse link.

7.5 Simulation Results

In this section simulation results for stationary mobiles without fading and power control is presented. This is followed by the received signal at mobiles in a seven cell network with fading included. Finally, Monte-Carlo simulation results for the outage probability of mobiles in a 19 cell network is compared between conventional, independent and combined beamforming of the arrays in handoff.

7.5.1 Stationary Mobiles without Fading and Power Control

In this section the SINR of three downlink adaptive arrays with independent beamforming is compared to three adaptive arrays with combined beamforming under stationary mobile conditions and without fading or power control. The geometry is shown in Figure 80. Four stationary mobiles are assumed with positions as given in Table 11. The signal to noise ratio is 15dB. The element pattern shown in Figure 8 is used. The boresight directions relative to the x-axis are 60°, 180° and 300° for arrays 1-3, respectively.

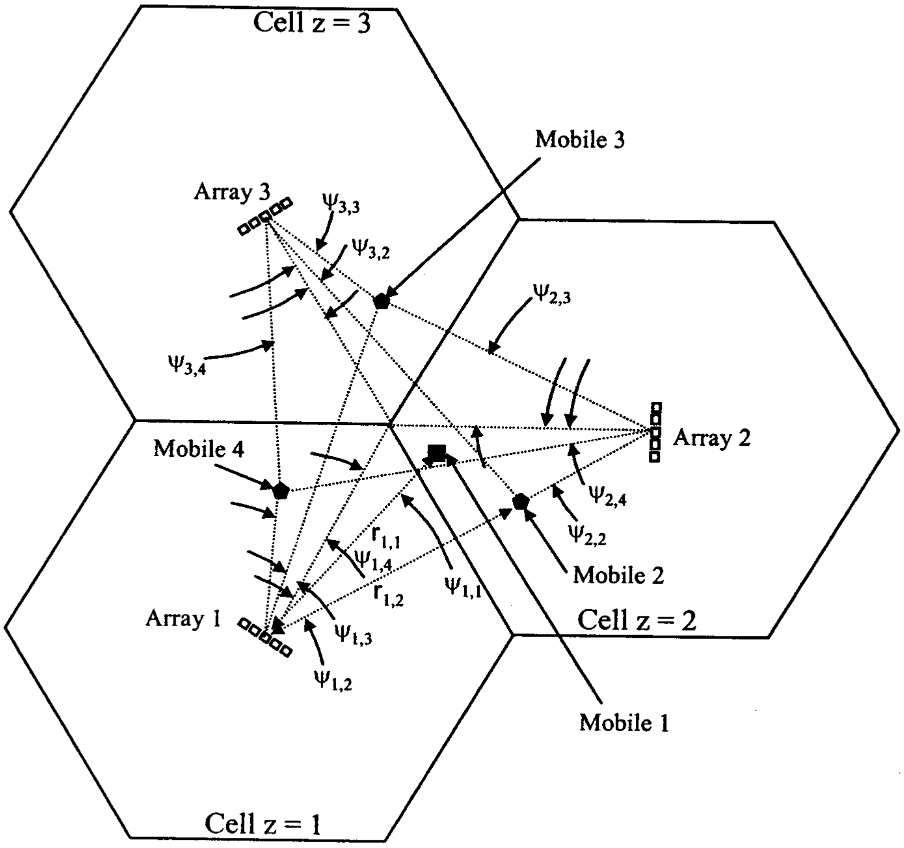

Figure 80: Geometry of three arrays and four stationary mobiles.

Table 11: Locations of the mobiles.

Mobile Number	Angle $\psi_{1,d}$ between array 1 boresight and mobile [degree]	Range $r_{1,d}$ between array 1 and mobile [relative to radius R]
1	15	R
2	40	0.87 R
3	-10	1.50 R
4	-45	0.87 R

7.5.1.1 Three Element Arrays

The received signal across the three cells for the SINR optimization of mobile 1 is shown in Figure 81 with individual array beamforming, and Figure 82 with combined array beamforming. It can be seen that the individual beamforming array is not able to reduce the signal towards all three interferers, while the combined beamforming arrays creates deep nulls in the vicinity of all interferers. The calculated signal to noise ratios for all four mobiles are given in Table 12 for individual and combined beamforming. The SINR is optimized for each of the four mobiles. The array signals are combined at the mobile with maximum ratio combining.

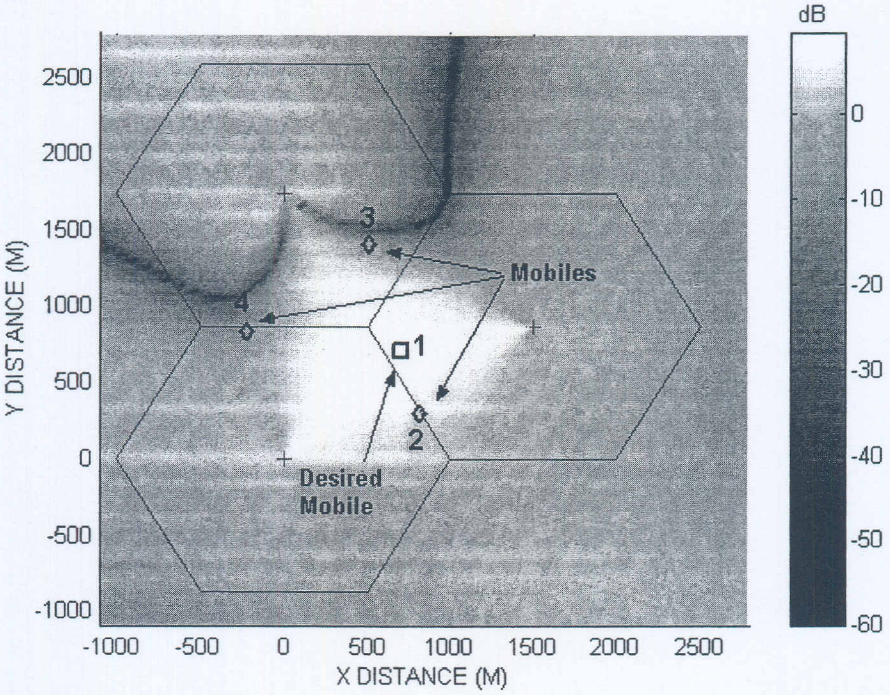

Figure 81: Received signal over three-cell network area for individual beamforming with three element arrays.

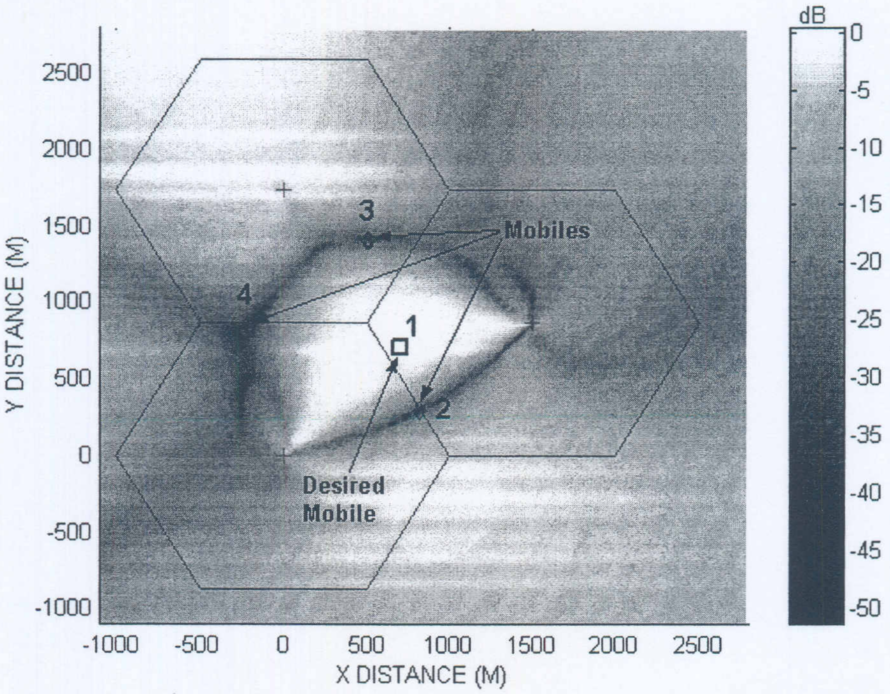

Figure 82: Received signal over three-cell network area for combined beamforming with three element arrays.

Table 12: SINRs at each mobile for independent vs. combined beamforming of three element arrays.

Beamforming method	Mobile 1 SINR [dB]	Mobile 2 SINR [dB]	Mobile 3 SINR [dB]	Mobile 4 SINR [dB]
Independent	-3.56	11.41	20.94	20.59
Combined	30.42	33.5	40.86	36.3

The independent beamforming arrays do not have enough resolution to separate the mobiles in angle, and therefore the SINRs for the independent beamforming arrays is low for mobiles 1 and 2 that are located close in angle. However, the SINRs at the mobiles with combined beamforming arrays are much higher (above 30dB).

7.5.1.2 Five Element Arrays

The received signal across the three cells for SINR optimization of mobile 1 is shown in Figure 83 for individual array beamforming, and Figure 84 for combined array beamforming with five element arrays. It can be seen that the both beamforming schemes creates deep nulls in the vicinity of the interferers. The signal to noise ratios for all four mobiles are shown in Table 13 for individual and combined beamforming.

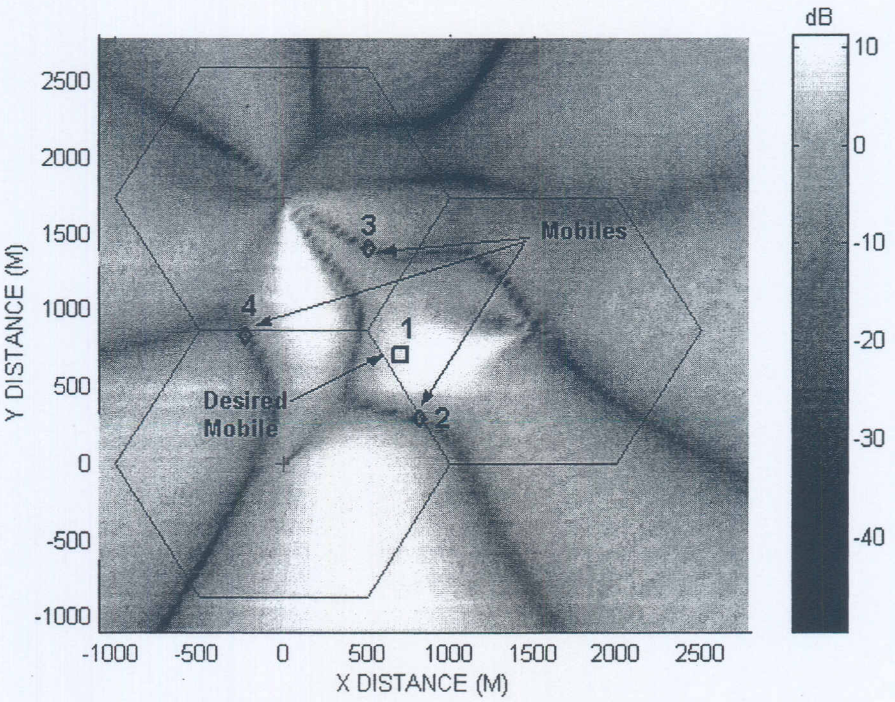

Figure 83: Received signal all over three-cell network area for individual beamforming with five element arrays.

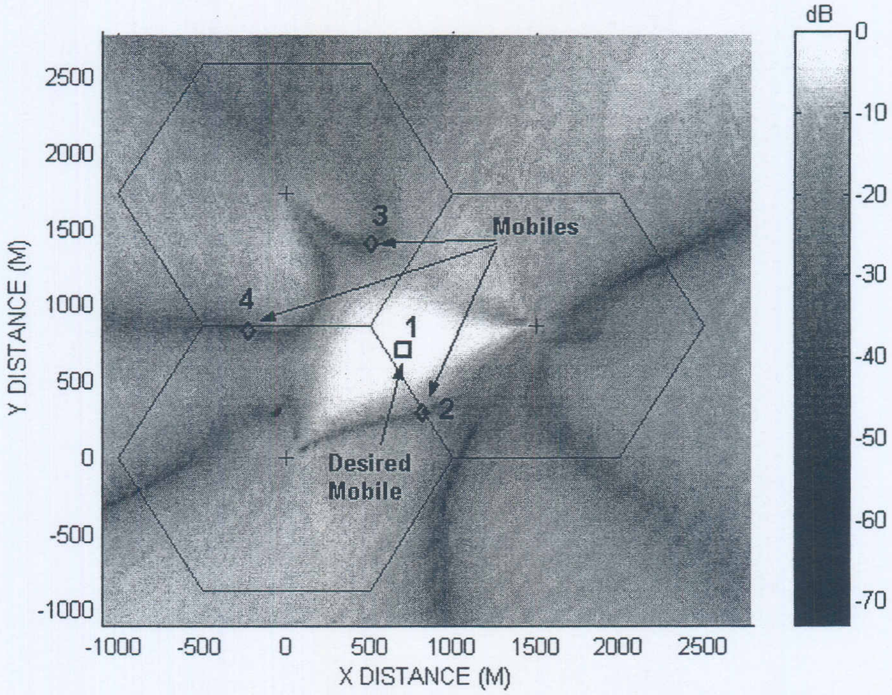

Figure 84: Received signal all over three-cell network area for individual beamforming with five element arrays.

Table 13: SINR at each mobile for independent vs. combined beamforming with five element arrays.

Beamforming method	**Mobile 1 SINR [dB]**	**Mobile 2 SINR [dB]**	**Mobile 3 SINR [dB]**	**Mobile 4 SINR [dB]**
Independent	37.81	37.9	39.7	41.8
Combined	44.4	37.9	42.5	39.5

In this case (five element arrays) the independent beamforming array resolution is sufficient to separate the mobiles in angle, and thus the SINRs of the independent beamforming arrays are all high. However, the SINRs of the independent beamforming arrays are generally lower (except for one mobile) than the combined beamforming array.

7.5.2 Received Signal Across Seven Cell Network With Fading Included

In this section an example of the received signal at all locations across a seven cell network is presented. The SINR is optimized for mobile 1, which is in a two-way handoff with sectors 1, 5 and 20. Rayleigh fading for each of the L multipath components is assumed and the incidence angles from the mobiles to all base station sectors are calculated based on the model in section 2.4. The simulation parameters are given in Table 14 and the array element pattern is shown in Figure 85. The received signal is shown in Figure 86 for independent beamforming and Figure 87 for combined beamforming.

There are one mobile per sector in this example, with the locations of the mobiles indicated in the figures. Since the signal at the desired mobile (mobile 1) is optimized, the received signal at this mobile must be high. On the other hand, the signals at the other mobiles must be lower in order to reduce the interference to them. It can be seen that the signal at the desired mobile is high for both independent and combined beamforming in the two figures. However, by visual inspection, it can be seen that the signals at the other mobiles is generally lower for combined beamforming. As an example, the signal at mobile 14 is approximately 10dB lower for combined beamforming relative to independent beamforming.

In the next section, a more quantitative comparison of the performance of the downlink of a CDMA system with independent beamforming versus combined beamforming of the arrays in handoff will be presented.

Table 14: Simulation parameters.

Parameter	Value	Unit
Number of cells	7	-
Number of mobiles per sector	1	-
Number of elements per array	7	-
Signal to noise ratio	25	dB
Angular spread standard deviation	5	degrees
Handoff threshold	-15	dB
Number of multipath components	3	-
Slow fading standard deviation	8	dB
Pathloss exponent	3.2	-
Voice activity factor	1	-

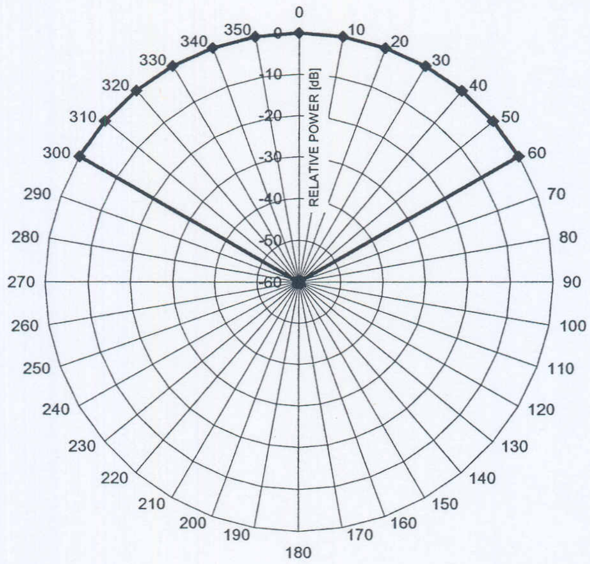

Figure 85: Element pattern that was used in the CDMA downlink simulations.

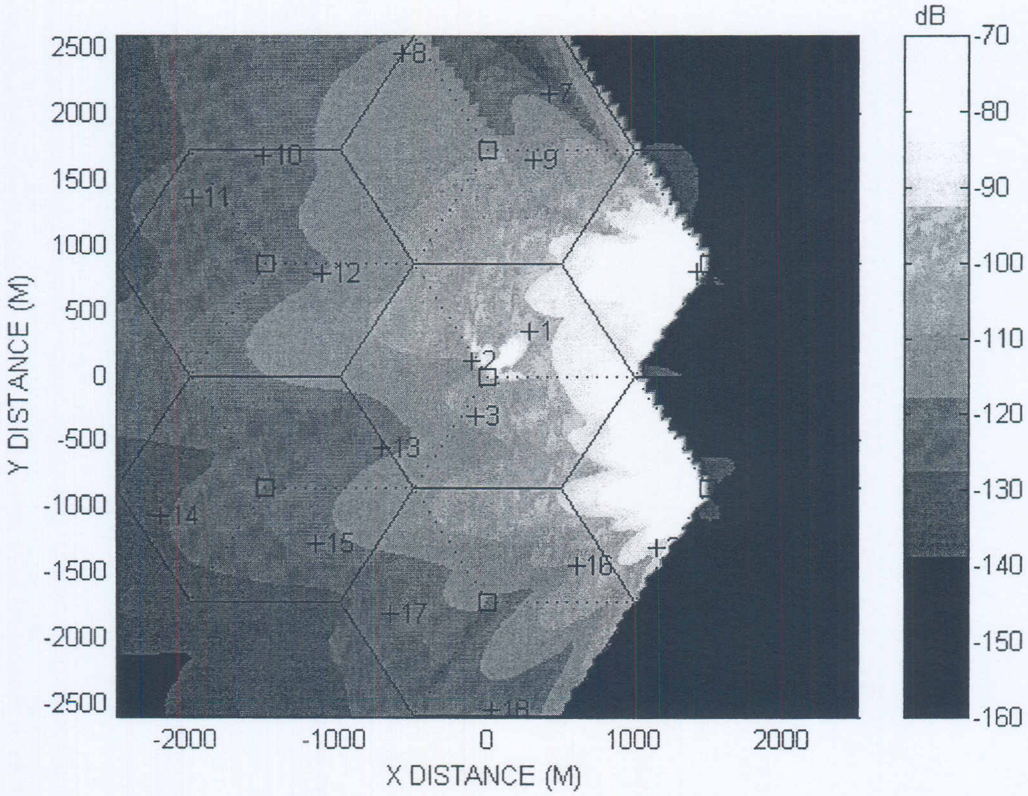

Figure 86: Received signal at all locations in a seven cell network with independent beamforming optimization for desired mobile 1.

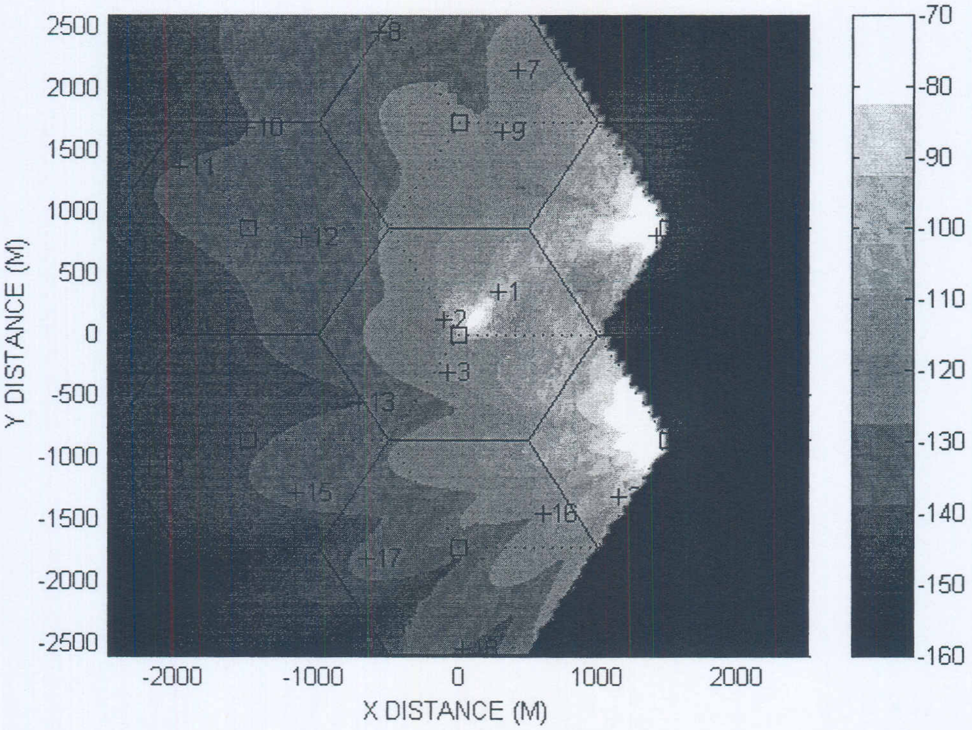

Figure 87: Received signal at all locations in a seven cell network with combined beamforming optimization for desired mobile 1.

7.5.3 Monte-Carlo Simulations

7.5.3.1 Procedure

A Monte-Carlo analysis is applied to estimate the outage probability of the CDMA network. The outage probability of a network with a 120° sector antenna is compared to a network with either independent or combined adaptive beamforming for the sectors in soft/softer[54] handoff. The outage probability is the probability that the signal to noise ratio is below a certain threshold [12,30], or:

$$Outage\ Probability = Probability(SNR < SNR_{Threshold}) \quad (210)$$

The threshold used in the simulations is 7dB, corresponding to a BER performance of less than 10^{-3} for BPSK (binary phased shifted) modulation [12]. The simulation flow diagram is shown in Figure 88. At each iteration, the mobile positions are randomly generated (with a uniform distribution across the sector), with a certain number of mobiles per sector. The voice activity factor for each user is determined, based on whether a uniform random number is below a certain threshold, indicating that the mobile is active. All active mobiles are assigned an initial transmit power of one and the inactive mobiles a power of zero. Rayleigh fading for each multipath component is assumed and the incidence angles from the mobiles to all base station sectors are calculated based on the model in section 2.4. Power control for each mobile is applied according to the received signal power level at each mobile (fading included), using the procedure that is described in section 7.3.

The sectors that are in handoff with each mobile are determined next. The sectors where the received pilot power (power before correlation gain is applied) relative to the total interference noise is above a certain handoff threshold, t_{HO}, will be added to the handoff list.

The weight vectors for the combined and independent arrays are determined next (see section 7.2). This is followed by the received signal to noise ratio calculation at each mobile. The power is re-adjusted for the mobiles in the network for both combined or individual array beamforming, again based on the received signal to interference ratios at the mobiles (see section 7.3). After the transmit power of the mobiles has been adjusted with the power control algorithm, the SINRs of all the mobiles are then calculated.

An error will be reported when the SINR of the desired mobile is below the threshold. The total number of errors for the sectorized, individual beamforming and combined beamforming arrays are calculated and divided by the total number of iterations. This ratio is then the outage probability for the specific network, based on the number of mobiles per sector.

[54] Softer handoff is used in CDMA to describe the handoff between sectors of the same base station, while soft handoff refers to handoff between sectors of different base stations.

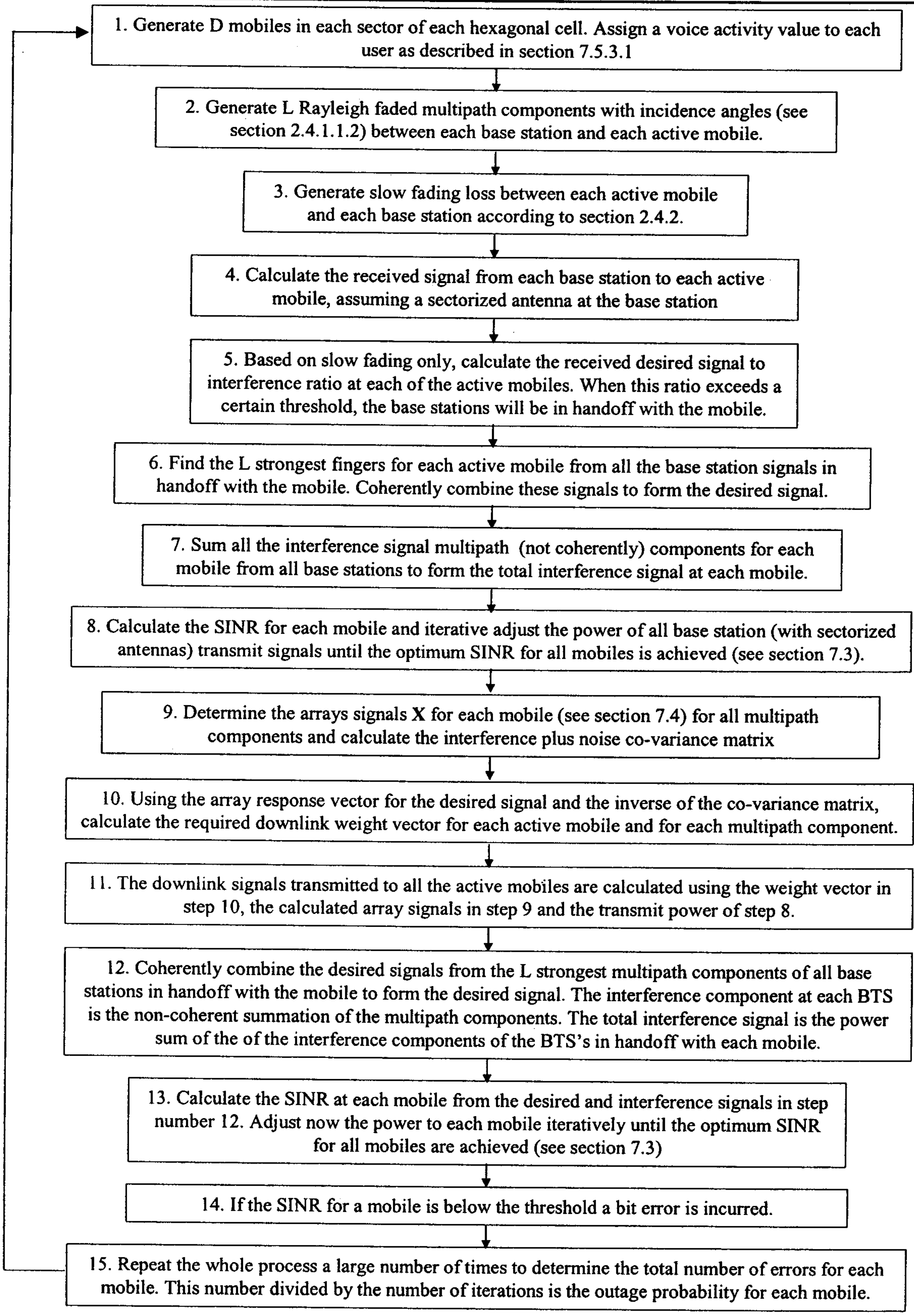

Figure 88: CDMA downlink simulation flow diagram.

7.5.3.2 Simulation Results

The simulation parameters are listed in Table 15, and the antenna element pattern that was used in the downlink simulations is shown in Figure 85.

Table 15: CDMA downlink outage probability simulation parameters.

Parameter	Value	Symbol
Signal to noise ratio	30 dB	SNR
Max number of power control iterations	25	-
Power reduction amount per power control iteration	0.7	-
Cell Radius	1000 m	R
Total number of cells	39	Z
Number of cells containing mobiles	7	-
Pathloss coefficient	3.2	γ
Angular spread standard deviation	2.5°	σ_{as}
Slow fading standard deviation	8 dB	σ_{sf}
Handoff threshold	-15 dB	t_{HO}
Desired signal to noise ratio	7 dB	$SNR_{Threshold}$
Processing gain	21.1 dB	g_p
Number of multipath components	3	L
Voice activity factor	0.375	ϑ

7.5.3.2.1 Results of a Single Run

The SINRs of the sectorized, independent and combined beamforming arrays will be compared for a single snap-shot of the mobile locations and fading conditions in this section. A total of 16 users per sector is considered, the angular spread is 5°, the voice activity factor is 0.375 and the number of elements per array is four. The positions of the mobiles and the number of handoffs of each mobile are shown in Figure 89. It can be seen that the number of handoffs range between no-handoff to two-way handoff[55]. The transmitted power (sectorized, independent beamforming and combined beamforming), SINR of sectorized antenna network before power adjustment and SINR after power

[55] Two-way handoff means that the mobile is combining signals form two base stations (or sectors).

adjustment of the sectorized, independent beamforming and combined beamforming networks are shown in Figure 90.

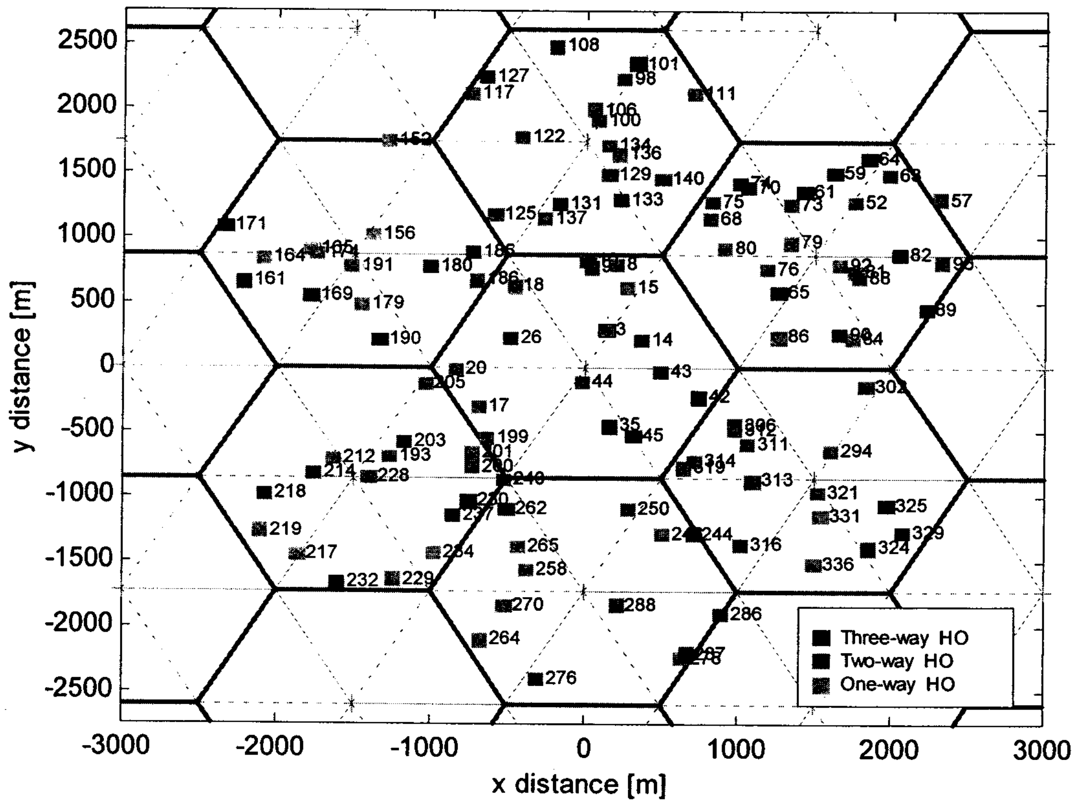

Figure 89: Mobile locations and number of handoffs experienced by each mobile for single iteration.

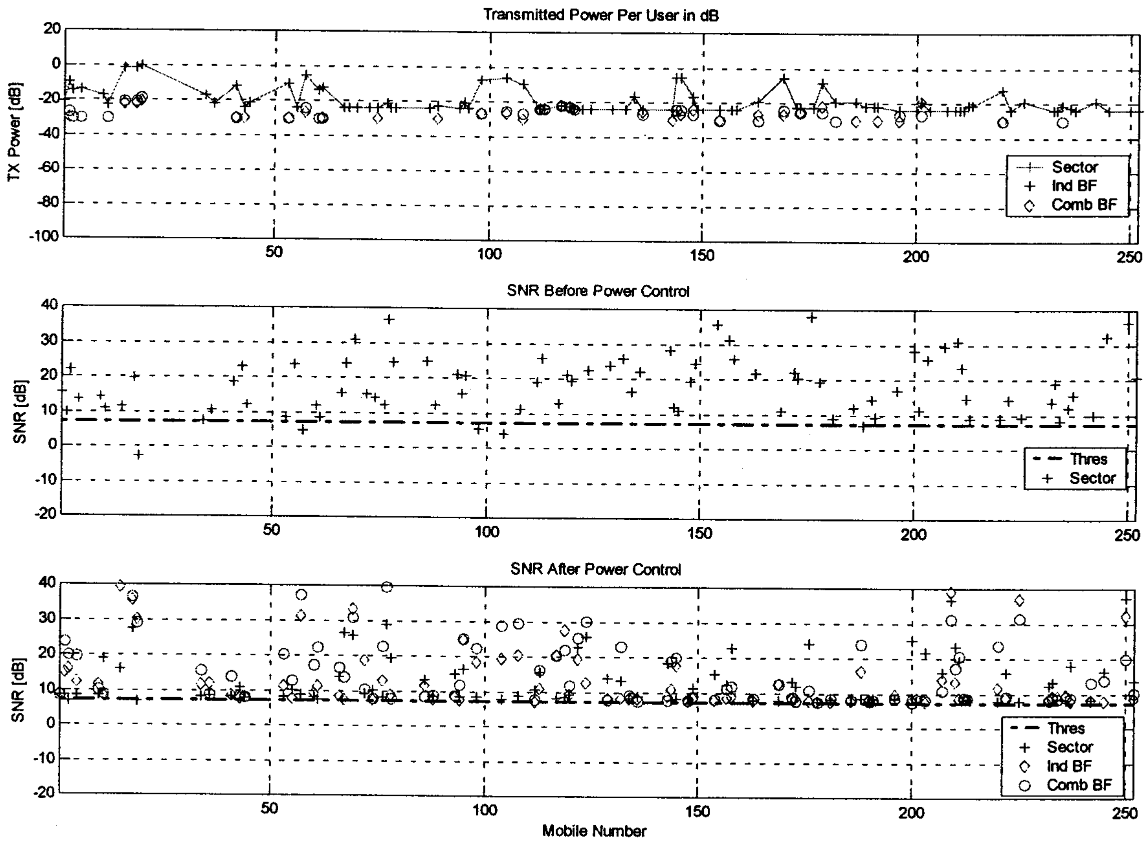

Figure 90: Transmitted power per user, SINR before power control, SINR after power control, SINR of combined beamforming compared to individual beamforming (four elements per array).

In this example the average SINR is 24.3dB for the sectorized antenna, 28.3dB for independent beamforming and 33.9dB for combined beamforming.

7.5.3.2.2 Outage probability estimation

The probability of an outage at the mobile as calculated with Monte-Carlo simulations are presented in this section. The simulation parameters are listed in Table 15. The outage probability as a function of the number of mobiles per sector of a sectorized antenna (reference) network as well as three element distributed arrays with independent and combined beamforming is shown in Figure 91.

The figure shows that the outage probability with the three element arrays is lower than with the sectorized antenna (which can be expected due to the interference reduction of adaptive arrays). In addition it can be seen that with combined array beamforming more mobiles can be sustained at the same outage probability compared to independent array beamforming. Specifically at a bit error rate of 1E-3 with three element arrays, seven more mobiles per sector can be sustained with the combined beamforming distributed array than with independent beamforming of the arrays.

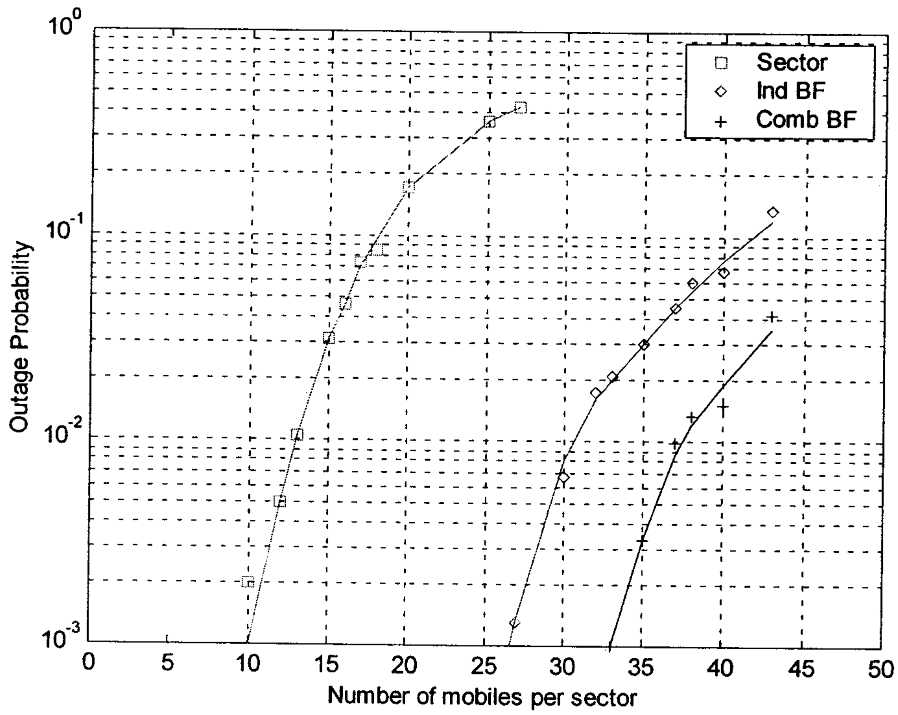

Figure 91: Outage probability as a function of the number of mobiles per sector for the CDMA downlink with sectorized antennas as well as independent and combined beamforming arrays (with three elements). The solid lines are an interpolation of the simulation values.

7.6 Conclusions

The aim of this chapter was to investigate whether there is an advantage in using combined optimum beamforming as opposed to independent beamforming for the arrays in handoff on the downlink of a CDMA system. The results for four stationary mobiles in two way soft handoff in a three cell network gave a minimum SINR improvement of 15dB with combined beamforming of the arrays in soft handoff relative to independent array beamforming (for three element arrays). None of the mobiles with combined beamforming has a SINR below 0dB, while one mobile has a SINR of approximately –5dB with independent beamforming. The five element arrays gave positive SINR for both beamforming schemes.

It was shown with Monte-Carlo simulations that the outage probability with combined beamforming of three element arrays results in a lower outage probability than independent beamforming of the arrays in handoff. The mobiles were randomly located in the cell. It was shown that at a bit error rate of 1E-3, seven more mobiles per sector can be supported with combined beamforming of three element arrays relative to independent beamforming.

8 CONCLUSIONS

8.1 Introduction

Spectral efficiency improvement of cellular networks is becoming an increasingly important means of enhancing network capacity. Spectrum efficiency is improved by increasing the number of mobiles operating on the same frequency channel. Network capacity is mainly limited by the received signal to interference ratio at the mobile and base station. Therefore, interference reduction results in an overall increase in the system capacity.

Adaptive, phased and multibeam arrays are widely studied as a means of significantly reducing this interference. The arrays will form, steer or select a beam that transmits the best signal to the desired mobile on the downlink while minimizing the signal to other users. Similarly, on the uplink the array beam will maximize the signal received from the desired user while minimizing the signals received from interfering mobiles.

In TDMA systems, adaptive array interference reduction allows for a smaller reuse distance up to the point where multiple users can operate on the same frequency and time slot (same cell frequency reuse). An adaptive array is able to reduce the signals to and from interfering mobiles even if they are in the same direction (relative to the array boresight) as the desired signal, provided the array element spacing is large or the propagation environment has a wide angular spread (or both). Large array element spacing is undesirable as it is difficult to install large arrays on towers and buildings due to esthetic, environmental and windloading considerations. Large user densities is typically associated with a wide angular spread environment (urban and dense urban), but there are many cases where the opposite is also true. This case as well as small interelement separations, limits the performance (and thus capacity) of same cell frequency reuse configurations.

The limitation in reduction of interference by center cell arrays with small interelement spacing from mobiles located close in angle to the desired mobile in a narrow angular spread environment can be overcome by moving the arrays to the corners of the cell. Each array can form a beam that will maximize the signal to interference ratio of the desired mobile, whereafter the optimum signal from all the corner arrays can be selected.

Alternatively, all arrays can form a combined beam, which will generally result in the best signal to interference ratio.

Code division multiple access systems (CDMA) on the other hand always has a same cell frequency reuse (with a reuse pattern of one). In soft handoff, signals from multiple base stations are used to reduce the slow fading loss between mobile and base station. Each base station in soft handoff independently forms an optimum beam. However, as with multiple array beamforming in TDMA systems, independent beamforming can produce non-optimum signal to noise ratios, depending on the specific propagation and user locations.

The range of phased arrays is a function of the array beamwidth and the angular spread of the propagation environment. If the phased array beamwidth becomes narrower than the angular spread, the range increase (relative to an omni antenna) is limited. The adaptive array does not have this range limitation, as the array adapts its beam to the incoming multipath components. The presence of interfering mobiles in a multipath environment affects the range increase of phased and adaptive arrays. The array interference reduction ability is affected by the propagation angular spread.

8.2 Relevance

Work in this thesis is an extension of work in the literature on same cell frequency reuse with adaptive arrays as a means of increasing the capacity of FDMA/TDMA cellular networks [4,5,6]. Studies in the past mainly considered antennas at the center of the cell, although some studies investigated the performance of antennas and arrays at alternative locations in the cell [7,8,9,37,38]. None of the studies specifically investigated the combined beamforming of spatially distributed arrays. In this thesis combined beamforming of multiple adaptive arrays at the edges of the cell was investigated.

The soft handoff benefits on the downlink of a CDMA system with sectorized antennas has been studied in [65], and with multiple antenna selection in [30]. The downlink performance of adaptive arrays in CDMA cellular systems is documented in [30]. Studies on the CDMA downlink performance with adaptive arrays in soft handoff is studied in [40,41]. The advantage of combined beamforming of the arrays is soft/softer handoff on the downlink of a CDMA system was studied in this thesis. Similar studies were not found in the literature.

Past studies investigated the range of phased and adaptive arrays in a multipath environment, excluding the effect of interference [45,56]. A comparison of the range increase of an adaptive array with a phased array in a multipath environment for mobile communication systems was published recently [16]. Work in this thesis elaborated on the study in [16] by adding the effect of interference on the range increase of adaptive and phased arrays relative to an omni antenna.

8.3 Contributions and Conclusions

The effect of interference on the range increase, relative to an omni-antenna, of adaptive and phased arrays in a multipath environment for both narrowband and wideband (spread spectrum) cellular systems was investigated. This work is an extention of the investigation in [16], where the effect of interference was not considered. The range increase of a narrowband cellular system with a single dominant interferer at various incidence angles was presented as a function of the number of array elements and scattering angular spread. The range increase of both adaptive and phased arrays are affected by the angular spread and the angle of the interferer relative to the boresight of the array. A significant reduction in the range increase of a phased array is visible in a narrow angular spread environment when the multipath angular components of the interferer starts to overlap with the array beamwidth. The adaptive array is able to reduce interference multipath components even if the interferer is in the same direction as the desired signal. Therefore, the range increase of the adaptive array exceeds that of the phased array for the same conditions (number of elements, angular spread and interferer locations). The range increase of wideband spread spectrums with twelve interferers per sector (typical for CDMA cellular systems) was presented as a function of the number of array elements, scattering angular spread and received signal to noise ratio. Similar to the results in [16], the range increase limitation of phased arrays in the presence of multiple interferers can be improved by using a weight vector optimized for each RAKE receiver finger. The results also showed that the range increase of phased arrays is less than that of adaptive arrays due to the lack of cancellation of interferer multipath components falling inside the beamwidth of the phased array.

A simplified analytical model for the probability density function of the angle of arrival of multipath signals was presented. Using this probablility density function, an analytical model was derived for predicting the range increase of a phased array in a multipath environment in the presence of a dominant interferer. The model includes the phased array asymptotic range limit when the beamwidth of the array becomes narrower than the angular spread of the desired signal. This limit is a function of the multipath angular spread.

The concept of the spatially distributed array was presented as a means of increasing the same cell frequency reuse capacity of the network beyond that possible with single adaptive array systems located at the center of the cell. Adaptive arrays at the center of the cellsite are limited in their ability to separate co-channel users from each other when they are closely located in angle relative to each other (as seen by the base station antenna) in a narrow angular spread (low multipath) environment with closely spaced antenna elements. A concept with multiple arrays located far apart in the cell (spatially distributed array) was introduced. This array consists of three sub-arrays at alternate corners of the cell and when applied to TDMA type networks has the ability to receive user signals from multiple viewing angles. It is therefore able to obtain an improved rejection of interfering signals relative to the arrays located at the center of the cell. This concept was published in [17, 18], where the reduction of the outage probability of a combined distributed array vs. the conventional array at the cell center in a non-multipath environment was presented.

It was shown analytically that the SINR with optimum combining of the sub-array output signals of a distributed array (after independent optimum beamforming of the sub-arrays) is equal to the sum of the SINRs of the individual sub-arrays with independent beamforming. Analytical expressions were derived to show that the SINR of a distributed array with two sub-arrays is greater or equal to the SINR of independent beamforming of the arrays for a single interferer. The result was extended to multiple interferers through numerical simulations.

The bit error rate and outage probability performance of spatially distributed arrays on the uplink of a TDMA cellular network in the presence of fast fading and shadowing was estimated by means of Monte-Carlo simulations. Combined beamforming of the sub-arrays was compared to independent beamforming as well as to conventional arrays at the center of the cell. The performance was investigated as a function of the frequency reuse pattern, number of antenna elements, multipath angular spread and power control. Fast and slow fading as well as a multi-tiered network interferers were included in the simulations. It was shown that for a reuse pattern of one with four element arrays, one same-cell co-channel users can be sustained in a GSM network (outage probability less than 1.8% and 3dB protection ratio) with optimum combining of the sub-arrays, while none can be supported with independent array beamforming or conventional arrays. With six element sub-arrays, two same-cell co-channel users can be sustained in a GSM network with independent array beamforming and three users with combined sub-array beamforming.

An analytical model for estimating the BER performance of spatially distributed arrays in a Rayleigh multipath environment was developed. This model is an extension of a model in [11] for determining the bit error rate performance of a single array in a multipath environment. The method is based on finding the Laplace transform of the probability density function (PDF) of the array output SINR through a generalized eigenvalue solution. The inverse Laplace transform then yields a simplified probability density function in terms of eigenvalues, which is applied to estimate the BER at the array output. The BER calculated with the derived analytical model is compared to the BER simulated with a Monte-Carlo method. A spatially distributed array with two-element sub-arrays and correlated fading between the array elements for each mobile signal is considered. It was shown that the analytical and simulated bit error rate results are in close agreement.

The concept of combined beamforming of arrays in handoff for the downlink of a CDMA network was formulated. A formulation for the downlink signals to the mobile from multiple base station arrays were presented. The formulation relies on an accurate estimation of the downlink propagation channel array response matrix. Techniques to etimate this matrix were discussed. Using the downlink formulation, the outage probability at the mobiles was compared by means of Monte-Carlo simulations between combined beamforming of the arrays in multi-way handoff versus independent beamforming of the arrays. The simulations included the effect of fast and slow fading as well as power control for a 19 cell network. It was shown that the outage probability with combined beamforming of three element arrays resulted in a lower outage probability than independent beamforming. The results specifically showed that for a bit error rate of 1E-3, seven more mobiles per sector can be supported with combined beamforming of three element arrays compared to independent beamforming.

8.4 Future work

The following suggests future work that can flow from this study:

- It was shown analytically that the signal to interference ratio is higher for adaptive arrays with combined beamforming than with individual beamforming in a non-multipath environment for a desired signal and single interferer. This analysis can be extended to multiple interferers.
- Closed form solutions were derived for the bit error rate of distributed arrays in a multipath environment. Although difficult, it may be possible to include the effect of slow fading on the BER of distributed arrays.
- The bit error rate and outage probability of distributed base stations with adaptive arrays was investigated for both TDMA and CDMA systems. The investigation can be extended to include the performance of distributed multibeam and phased arrays.
- It was shown with Monte-Carlo simulations that the outage probability is lower for combined beamforming than independent beamforming of the arrays in handoff in a CDMA network on the downlink. The investigation was done for the case of three element arrays with 2.5 degree angular spread. The investigation can be extended to more antenna elements and wider angular spreads. Multibeam and phased arrays can also be included in the study.
- Instead of Monte-Carlo simulations, closed form solutions for the outage probability of CDMA systems with combined beamforming of adaptive arrays in handoff may be derived when applying some approximation
- In the CDMA downlink simulations it was assumed that the propagation channel between the base station and mobiles can be accurately determined by means of an adaptive method using feedback from the mobile. The effect of errors in this estimation can be investigated.