CDMA Array Processing

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Abstract

Base station antenna arrays are a promising method for providing large capacity increases in cellular mobile radio systems. This paper considers receiver structures and algorithms to examine the potential capacity gains from the employment of multiple receiver antenna elements in the range one to eight for code division multiple access (CDMA) systems.

1 INTRODUCTION

Personal (cellular) communication systems (PCS) have become a significant area of growth within the last few years. There are a diverse range of products and services currently on the market, but PCS radio networks probably have the highest public profile. These services provide highly-mobile, widely accessible two-way voice and data communications links [1]. It is now generally accepted that as we progress from current 2nd generation TDMA/CDMA standards for voice communication we will move to providing a range of data rates - from 144 kbit/s through to 2 Mbit/s with the higher rates only being available to pedestrian and indoor low mobility users. The most complex and expensive part of the radio path for these personal cellular systems is the base station. As a result, manufacturers have been designing networks which have high efficiency in terms of the bandwidth occupied and the number of users which can be accommodated per base station [2].

Considerable system capacity gains are available from exploiting the different spatial locations of cellular users [3,4,5]. This gives rise to the concept of the smart or intelligent antenna. There are a number of methods to achieve this, from simple fixed beam sectorisation schemes [6] to complex adaptive antenna array techniques [7]. Adaptive antenna arrays have previously been a heavily researched area in the 1960s and 1970s [8-11]. This paper will consider antenna arrays for the mobile-to-base station or reverse link of a CDMA cellular system such as the IS-95 standard [12]. It begins with an introduction to CDMA communications systems and also addresses the general topic of antenna array receivers. Channel modelling is then discussed, as this will influence the design of CDMA receivers. The specific form of receiver algorithms will then be discussed and some performance comparisons are provided. Finally, the most important question for implementing antenna array systems is the capacity gains which are achievable.

2 DIRECT-SEQUENCE CDMA

Spread spectrum communications, were originally developed for military applications. A simple definition of a spread spectrum signal is that its transmission bandwidth is much wider than the bandwidth of the original signal [13]. In these early systems the multiple access or CDMA aspects were not actively addressed. Recently these techniques have been revisited for mobile cellular systems where the reverse links for all users within a CDMA system are accommodated over the same radio frequency (RF) bandwidth, so that complete frequency re-use for that link is obtained throughout all cells. To distinguish one user's transmission from another, each mobile modulates the voice data symbols by a pseudo-noise (PN) code. Each symbol is composed of W binary "chips" which have a much shorter period than that of the original data symbols, so that the signal bandwidth is considerably increased.

The reverse link of a CDMA system, such as that specified by IS-95 [12], has a number of essential characteristics for effective multiple access communication. A detailed introduction to spread spectrum and CDMA techniques can be found in [12-14], but here only selected points will be addressed.

2.1 Spread Spectrum Bandwidth

The chip rate of the spread spectrum signal is inversely proportional to the chip period t_c. A number of different chip rates have been proposed for such systems, but a chip period of approximately 800 ns (chip rate 1.25 MHz) will be assumed for this paper. Such a system is often called *narrowband* CDMA, because the baseband bandwidth is much smaller than the 900 - 1800 MHz RF carrier frequency, and 3rd generation PCS systems will be wideband, i.e. with chip rates of 5-20 MHz.

2.2 Multipath Diversity

In urban areas, multipath propagation is common, whereby the receiver observes a number of copies of the transmitted signal, each with a different time delay. This provides a form of multipath diversity, which can be exploited by using a RAKE receiver at the output of the code correlators [15].

2.3 Asynchronous Operation

The reverse link of a CDMA system is usually asynchronous, in the sense that the arrival times for each user's code are different. This means that the receiver for each user will observe interference from all other users in the system, as the transmitted codes will not be orthogonal. Hence, the number of users that can be simultaneously accommodated in one cell is *interference-limited* and, in general the reverse link thus has less user capacity than the synchronous forward link.

2.4 Power Control

It has always been known that to operate effectively spread spectrum systems must experience similar received user power levels as the discrimination between users relies on the correlation properties of the (PN) spreading codes. In cellular systems power control is thus essential on the reverse link, to minimise multiple access or multi-user interference. Otherwise, mobile transmitters far away from the cell's base station will be swamped by interference generated by larger signal level users closer to the receiver. If all signals arrive with the same received power level, the receiver's tolerance to CDMA interference is proportional to the *processing gain* [13] $W = t_s/t_c$, where t_s is the symbol period for the slow speed traffic data bits.

The obvious way to increase the capacity of a CDMA system is to reduce the levels of multiple-access interference. In this paper, an approach based on antenna array receivers will be considered.

3 WHY USE A RECEIVER ARRAY?

An antenna array consists of M identical antenna elements, whose operation and timing is usually controlled by one central array processor. The geometry of the antenna locations can vary widely, but the most common configurations are to place the antennas round a circle (circular array) or along a straight line (linear array). Antenna arrays have frequently been proposed for the operation of RADAR and communications systems in a military context [8-11,15]: it is possible to perform direction finding tasks and to null or cancel out enemy interferers. However, in the context of civilian cellular systems, the aim of the antenna array receiver is purely to provide acceptable error performance and hence maximise the signal-to-interference and noise ratio (SINR) for each user in the system. An antenna array containing M-elements can provide a mean power gain of M over white noise, but suppression of interference from other cellular users is dependent on the form of the received data and the array signal processor which is employed [5].

Figure 1 shows the resulting beam patterns for linear arrays with different numbers of antenna elements. As the number of elements or array aperture increases then the mainbeam width reduces.

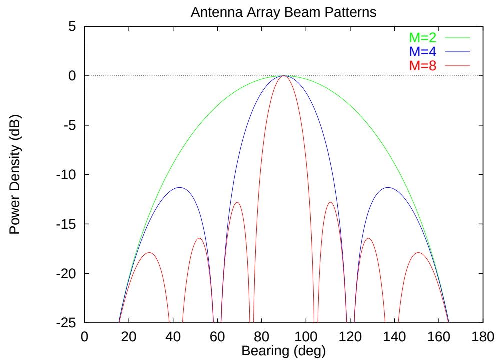

Figure 1 - Array beam patterns for 0.5 λ element spacing for $M = 2$, 4 and 8 elements.

In a power controlled CDMA system the strong desired signal is thus corrupted by a large number of smaller cross-correlation interference terms, which arrive with typically a uniform distribution from throughout the cell. TDMA arrays can usually null out $M - 1$ interferers, but for a CDMA system this is unlikely to improve significantly the received SINR [7] because of the very large number of interference components. In general, a better methodology is to estimate the form of the received signal and determine the matched filter solution [16]. This form of receiver can exploit any spatial diversity present, while suppressing the mean level of CDMA interference by a factor proportional to M. Assuming that the antenna array provides significantly improved SINR levels at the base station receiver, the number of channel errors, measured by the bit error ratio (BER), will reduce. This provides the cellular operator with some degrees of freedom which may be used for the following purposes [7,5]:

- To increase the number of active users for a given BER or probability of bit error quality threshold
- To reduce the SINR required at each antenna to achieve a target BER; this would reduce the transmit power required by the mobile handset for the reverse link

- To improve the BER performance for a given number of users within a cell
- To permit a less stringent form of reverse link power control whilst maintaining acceptable BER performance
- To increase the range of the base station receiver and thus the cell size reducing the installed equipment cost.

The concept of smart antennas [4] encompasses array processing receivers which are able to alter their radiation pattern in response to the environment in which they operate. This permits them to improve the reception of wanted signals under adverse multipath conditions and in the presence of unintentional interference from other users on the same frequency allocation (e.g. the re-use cells in a cellular system). Smart antennas will primarily be employed at the base station, since here their cost can be spread across the many subscribers within the cell.

Many techniques can be exploited by the smart antenna, including diversity combination to mitigate the effects of multipath, agile beam steering and null steering to improve performance against interference. The smart antenna problem to improve the reception of the uplink transmissions at the base station is the easiest to manage since here the base station receiver is able to provide an appropriate characterisation of the multipath channel. In order to fully utilise the improved uplink performance offered by the smart antenna, the downlink performance (from the base station to the mobile or customer premises) must be similarly improved, so that a balanced system is obtained. This is difficult, however, because the gain provided by the smart antenna at the base station cannot be provided (in the form of multi-element antenna array processing) at the mobile or the subscriber premises; also, for frequency division duplex system, the frequency offset between the up and down link transmissions means that the smart antenna solution derived for the uplink may be inappropriate for the downlink. An optimum solution to this downlink problem is as yet unknown. Another approach is to recognise this imbalance and simply reallocate more than half of the total available bandwidth to the downlink.

While smart antenna processing provides many advantages, these must be offset against the cost and complexity of their implementation. There are a number of points which must be taken into account here [17]:

- The hardware/software requirements increase as M demodulators are required for each user
- The computational complexity of some of the array processing algorithms can be very expensive
- The M receivers must be accurately synchronised in time to provide effective performance
- The array size will be constrained by the available space for a base station. Usually, the spacing of antenna elements varies from one half to tens of RF carrier wavelengths
- Antenna arrays may be adversely affected by channel modelling errors, calibration errors, phase drift and noise which is correlated between antennas.

With these points in mind, this paper will now consider channel modelling aspects of antenna arrays. This will motivate a discussion on the likely form of the processor to be employed in the CDMA antenna array base station receiver.

4 CHANNEL MODELLING

There are many different types of channel model appropriate to different radio systems and scenarios, but here a channel model will be developed for a large CDMA macro-cell operating in an urban environment. For simplicity, the case of a single antenna receiver will be initially considered: the results will subsequently be generalised for an antenna array receiver in the next section.

The radio channel can be characterised via its impulse response. This provides an indication of the severity of *multipath* propagation, which occurs due to multiple copies of the signal arriving at the receiver with different amplitudes and time delays. In dense urban areas, there are many buildings and obstacles that give rise to multipath propagation and the range of times of arrival can be significant. The COST-207 model is one widely used method of characterising the mobile channel [18].

It is often assumed that each channel tap is wide-sense-stationary for the mobile moving over short distances, up to a few tens of carrier wavelengths. This means that the signal variation with location, Figure 2, is due purely to phase changes in a set of independent multipath components which cannot be separated in time [19]. The resolvable channel taps are assumed to be uncorrelated as each tap arises due to contributions from different multipath scatterers.

The exact distributions of the signal envelopes are a function of the signal bandwidth but, for a narrowband CDMA system, two distributions are often proposed. If a dominant line of sight (LOS) path exists between the transmitter and receiver, the first received signal component will follow a Rician distribution. However, in urban areas, this is often not true: each channel tap consists of a number of independent multipath scatterers with the same probability distribution. Applying the central limit theorem, the received signal envelope statistics can be assumed

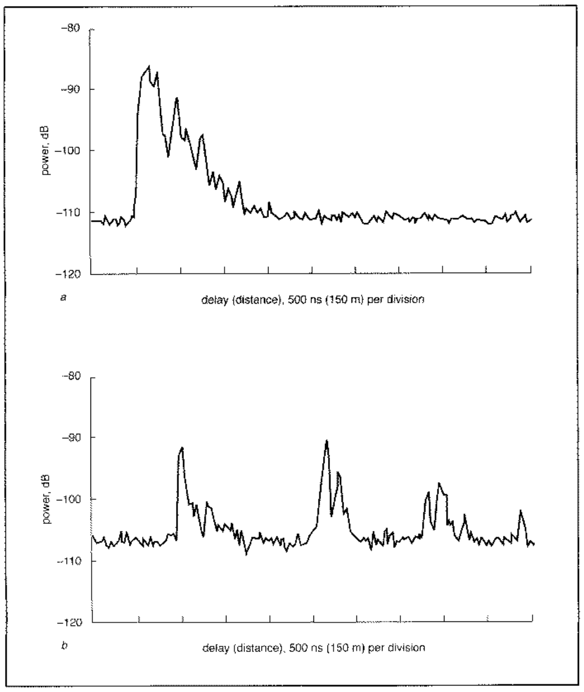

Figure 2 - Typical power delay profiles for two suburban sites in Edinburgh, after Ward [20]

to follow the Rayleigh distribution. As the mobile moves, the signal strength regularly changes by 20-30 dB, Figure 3, a phenomenon often called *fading*.

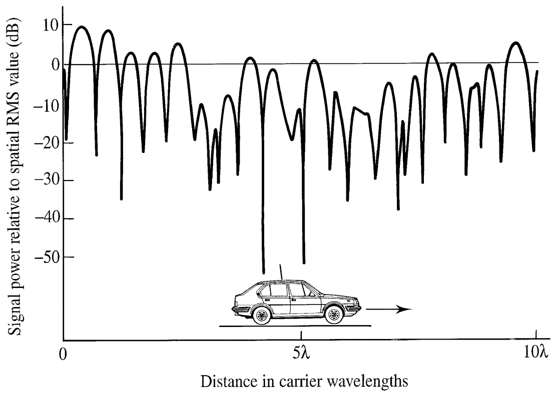

Figure 3 - Typical received power profile for a moving vehicle in a multipath environment

Over a longer period of time, the average (averaged over the Rician or Rayleigh fading) received signal power levels vary according to shadowing effects, which have been found to follow a log-normal distribution. The standard deviations quoted for this distribution vary between 4-12 dB according to the type of environment encountered [21]. In addition, the average received power varies inversely with the transmitter-receiver distance R, raised to the power n. Again, the value of n varies widely, but for urban areas its value is often approximated as 4 [19]. In this paper, it will be assumed that power control can adequately compensate for these effects but that it is unable to compensate for Rayleigh "fast" fading: this is somewhat pessimistic compared to the quoted results for IS-95 power control systems [12].

The overall time variation of the received signal, Figure 3, and the individual channel taps depends on the motion of the mobile. As the mobile moves through spatial locations with different field strengths, each multipath component of the received signal is subject to a Doppler shift in frequency. For a CDMA signal not subject to data modulation, calculating the power spectrum of each channel tap shows the distribution of Doppler frequencies for the constituent multipaths. The maximum Doppler frequency v_m is proportional to the vehicle speed v, according to the equation:

$$v_m = v/\lambda \qquad (1)$$

where λ is the carrier wavelength. There are two different forms of multipath scattering, according to the excess time delay of the given channel tap [14]:

4.1 Small Excess Time Delays

The channel tap may be modelled as the accumulation of multipath components received from scatterers close to the mobile. This gives rise to the classical Doppler power spectrum of the received multipath components, which is illustrated in Figure 4. The equation for the Doppler power spectrum $S(v)$ is given by [19]:

$$S(v) = \frac{a}{1 - \left(\dfrac{v}{v_m}\right)^2} \qquad |v| \le v_m \quad (2)$$

where v is the Doppler frequency and a is a scaling factor.

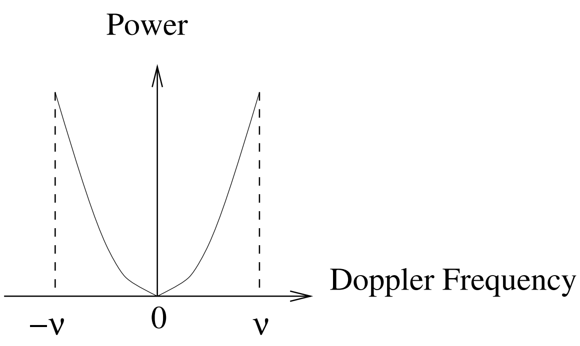

Figure 4 - Classical Doppler model for an unmodulated carrier

4.2 Large Excess Time Delays

The classical Doppler model does not provide a satisfactory geometric model for this type of scattering. Instead, multipath energy is more likely to have a narrow Doppler spread, having arisen from reflections off isolated obstacles such as buildings or hills.

The instantaneous variation of signal power in space for a channel, Figure 3, depends on the angles of arrival of the multipath components. The distribution of multipath energy with angle has been simulated using several different methods in the literature. Lee [22] used a model based on a cosine function raised to a high power to represent the angular width (or angle spread); a Gaussian distribution of multipath energy with angle has also been used [23]. However, one of the simplest models is due to Salz and Winters [24], who use a uniform distribution of energy with angle - this model will be used for the remainder of this paper. The angular width depends on the scattering circle diameter D and the distance to the base station R, Figure 5. The centre bearing is simply that of the mobile; for scattering with large excess time delays, a similar geometry applies replacing the circle of scatterers with the reflector giving rise to that component.

Table 1 [5] gives typical delay, angle and Doppler spread for multipaths in different cellular environments. This bearing dependant scattering has been previously measured with an aperture analyser and reported in [20] with typical measured results.

Environment	Cell type	Delay	Angle	Doppler
Flat rural	Macro	0.5 μs	1°	190 Hz
Urban	Macro	5 μs	20°	120 Hz
Hilly	Macro	20 μs	30°	190 Hz
Dense urban	Micro	0.3 μs	120°	10 Hz
Indoor	Pico	0.1 μs	360°	5 Hz

Table 1 Typical multipath channel parameters, after Paulraj [5].

Figure 5 shows a typical scenario where the scatterers are assumed to lie on a ring around the mobile transceiver.

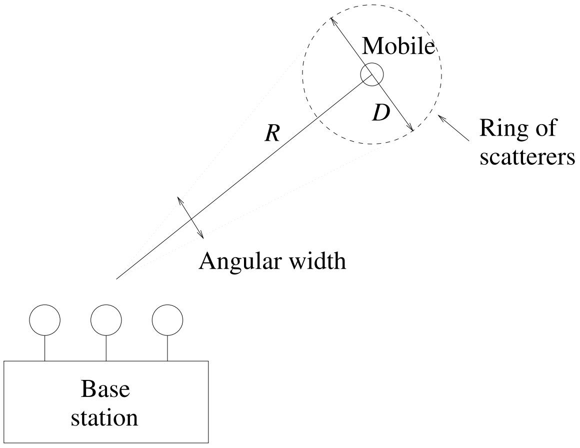

Figure 5 - Scatterers around the mobile defining, actual range R, mobile range R/D and width, 2Δ.

5 SMART ANTENNA PROCESSING

The antenna array must now process, in an optimal manner, a number of received copies of the desired signal, each of which is corrupted by undesirable interference. If there are K significant channel taps observed at the M elements of the array, i.e. 3-4 in Figure 2(b), there are $K \times M$ separate data samples to be considered when making a decision on each transmitted symbol. This situation requires what is called a ‘‘multichannel’’ receiver - it is equivalent to receiving the information over $K \times M$ separate narrowband flat-fading channels. The best approach to this problem is to weight each channel appropriately and combine them together, before making a data decision.

In this section, methods for combining an arbitrary number of channels in a smart antenna [4,10] will be considered - in the next section, specific receiver structures will be described. The main difficulty in designing such a receiver is to decide how to weight each data sample before combining in the beamformer matrix processor. There are many approaches to this problem, but here four fundamental methods will be discussed [7]:

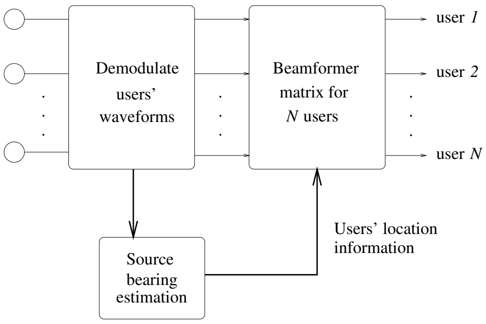

Figure 6 - The smart antenna concept [4]

5.1 Selection Diversity

If the receiver has to process a number of multichannels simultaneously, one method is simply to choose the multichannel which is presumed to have the largest signal power. This approach is quite simple, whilst permitting some performance improvement over single antenna receivers. However, this method does not provide the optimum improvement in SINR that can be obtained with the following techniques.

5.2 Maximal Ratio Combining

If the interference observed on each separate multichannel is assumed to be uncorrelated, maximal ratio combining is the method which maximises the SINR of the combined signals. This is particularly effective with $\lambda/2$ spaced antenna elements in a wide angle spread scenario.

5.3 Non-coherent Combining

If the receiver employs DPSK detection, the carrier phase reference is simply the data sample obtained for the previous symbol. The magnitude of the previous data sample also provides an estimate of the signal amplitude, so the multi-channels may be combined as follows:

$$\hat{d}(n) = \sum_{i=1}^{L} \{z(i,n)\, z^*(i,n-1)\} \qquad (3)$$

where $\hat{d}(n)$ is the estimate of the current transmitted symbol, z^* indicates the complex conjugate operation on the real part of a complex number. As the combiner weights $z^*(i,n-1)$ are noisy, the SINR of the combined signals tends to be poorer than for maximal ratio combining. For currently used dual diversity antennas ($L = 2$), the loss in SINR at the system operating point is typically less than 1 dB: however, as L increases the losses become greater.

5.4 Wiener Filtering

The three techniques described so far are based on maximising the signal power at the combiner output. It is also possible to use a Wiener filter [25], which attempts to suppress interference and maximise the SINR at the combiner output. The performance of this technique is likely to be better than that for maximal ratio combining when the interference is correlated between multichannels. This technique is discussed in more detail subsequently.

6 SMART ANTENNA RECEIVERS

The antenna array receiver aims to estimate the transmitted data sequence $d(n)$, based on the interference corrupted measurements from the K channel samples. There are two approaches that can be considered for combining the data samples. In a single antenna CDMA receiver, non-coherent combining is often used to combine the K channel samples, a method which is normally called RAKE filtering [15]. A simple approach to designing an antenna array receiver is to employ a RAKE filter to combine all the $K \times M$ received data vectors. For DPSK modulation, this is performed using equation (3) with $L = K \times M$. However non-coherent combining of a lot of multichannels can give rise to large losses in SINR compared to maximal ratio combining.

6.1 2D RAKE Filter

A more effective and compact approach to dealing with the channel tap vectors is to apply a separate spatial filter to each tap vector in turn. The receiver can exploit any structure that might be present, such as the directions of arrival of the multipath components, their Doppler frequencies, etc. This permits

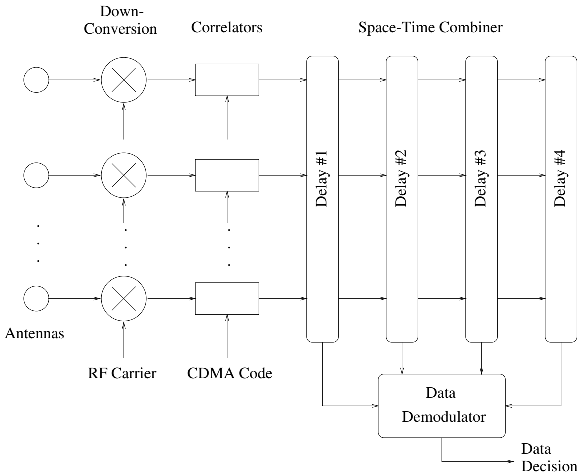

Figure 7 - Space - time combiner structure.

the receiver to perform coherent combining of the tap vector elements, improving performance over the 1D RAKE filter of [15]. This means that only K outputs need to be combined using the DPSK demodulation method of equation (3). The approach has been called the 2D-RAKE filter, because the receiver operates two separate sets of combiners in time and space. It is shown in Figure 7: the receiver picks out the largest channel taps and selects appropriate spatial filters in each case. The parameter K applies to the delays in Figure 7. The outputs from the spatial filter banks are then combined in a conventional RAKE filter, ready for decision-making. Base-stations are frequently split into three sectors, to provide 120° coverage, which in this case corresponds to the bearings [30°, 150°].

There are a number of methods to determine the form of the spatial combining filter weights. Many of these techniques employ the estimation of the covariance matrix $\hat{\mathbf{R}}_k$ of the signal [10]. This task may be performed by without the transmitter employing an initial training sequence by using blind channel identification techniques, such as:

6.2 Beamspace Transformation

This simple technique applies fixed spatial filters or beamformers to achieve a modest improvement in performance.

6.3 Bearing Estimation Techniques

As the received vector is composed of a number of steering vectors, it is possible to apply bearing estimation techniques to the covariance matrix $\hat{\mathbf{R}}_k$ to pick out the major directional components, to determine the direction of arrival (DOA) as proposed in [26]. There are a number of well known high-resolution techniques such as ESPRIT and MUSIC [17]: however, these algorithms have to average over a number of received samples and they perform poorly in the presence of highly correlated multipath signals, which frequently occur in the urban communication channels. A simpler approach is to use the conventional beamformer approaches.

6.4 Eigenfilter Techniques

In order to identify the received signal vector it is possible to calculate the eigenvalue decomposition of $\hat{\mathbf{R}}_k$. Provided the SINR is large, the $M \times 1$ eigenvector $\mathbf{u}_1$ corresponding to the largest eigenvalue of $\hat{\mathbf{R}}_k$ then provides an estimate of the received vector using the statistical method of principal component analysis in [27]. This method thus maximises the SINR to provide a more optimal solution.

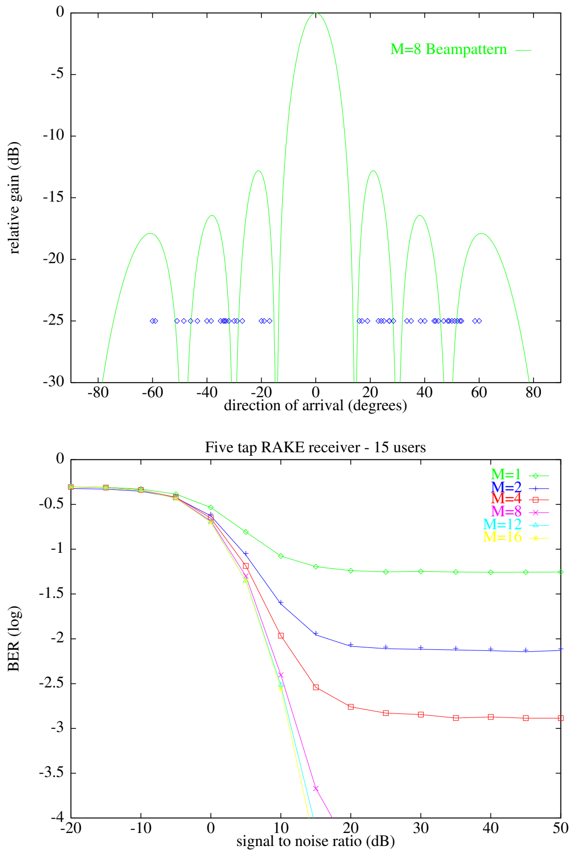

Figure 8 - User distribution where all the interferers lie on the sidelobes of an $M = 8$ array beamformer.

6.5 Simulations

Figures 8 and 9 show two extreme signal scenarios for cells with 15 interfering users each with the 5-tap fixed multipath channel:

$$H(z) = 1 + 0.5\, z^{-1} + 0.25\, z^{-2} + 0.125\, z^{-3} + 0.06225\, z^{-4} \quad (4)$$

with the interfering multipath distributed over a range of azmuth angles. The figures show the interferer layout, with the desired user on boresight and the resulting BER or probability of bit error for a simple tapped delay line RAKE filter [15] with 1 to 16 individual receiver antenna elements. Figure 8 shows a good user distribution with angle while Figure 9 is less advantageous.

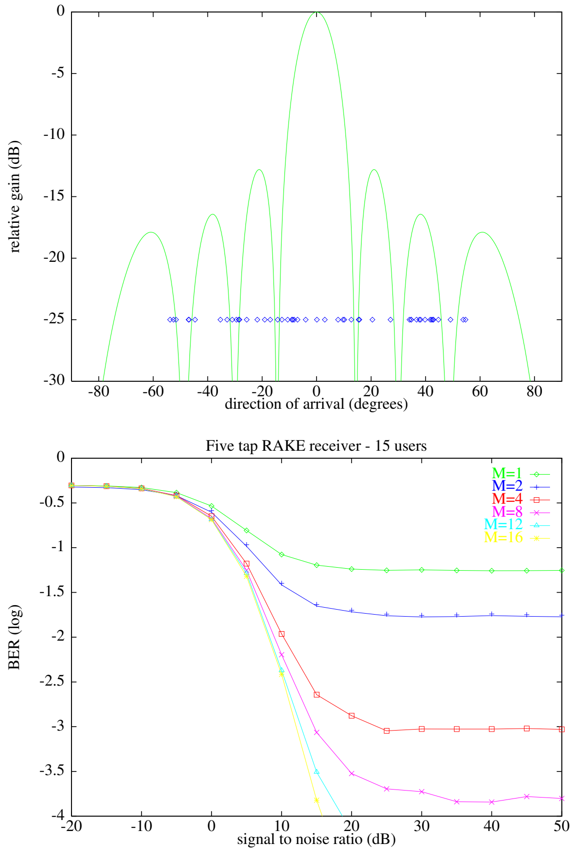

Figure 9 - Typical user scenario where the interferers are more uniformly distributed in angle.

Figure 10 shows the performance of a 1 GHz receiving system employing an 8-element 0.5 λ spaced array where 50 received data symbols are used to estimate the signal scenario. With this 8-element antenna the array gain is 9 dB and the theoretical output SINR is 14 dB. A 1-D RAKE filter would achieve approximately 11 dB SINR. The results for 0 Hz Doppler after 10,000 averaged simulations show excellent channel estimation performance over a range of angle spreads with the DOA algorithm gradually degrading with spread. The fixed beam performance peaks when the angular spread of the scatterers is well matched to the width of the 8-element beampattern. In comparison at 200 Hz Doppler there is a significant change in the signal scenario over the 50 sample window, degrading particularly the eigenfilter channel estimation which performed so well at the lower Doppler.

Further performance plots on these advanced smart antenna algorithms are to be found in [28,29] and in

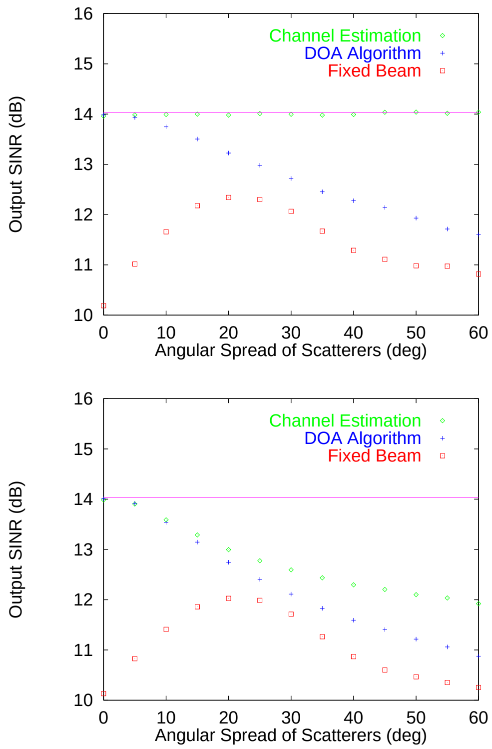

Figure 10 - SINR against scatterer angular width for the eigenfilter (channel estimation), bearing estimation (DOA) and fixed beam techniques at upper 0 Hz and lower 200 Hz Doppler frequency.

the extensive reference list accompanying [5]. It is clear that in Doppler there is an optimum number of samples to average over to minimise the combiner losses before the fast fading channel estimates change due to the motion of the mobile terminal, Figure 3.

6.6 Summary

The beamspace and bearing estimation (DOA) techniques essentially point narrow beams at the incoming signals from the mobile. This choice is optimal only if each channel tap appears as a point source. If multipath scattering of the signal gives rise to a significant angular width of the signal, the performance will degrade as the M element beamformer has only $M - 1$ unique beams which are insufficient to handle each of the major signal components. However, the eigenfilter method gives weights that maximise the combiner signal power, so it performs better in the presence of significant angular multipath spread. However, at low SNR, there is little benefit over the simpler bearing estimation techniques.

When the signal power of a given tap is not significantly larger than the interference power, the above techniques are likely to incorrectly pick out an interference instead of the desired tap vector. However, given that CDMA interference generally comprises the contributions of a large number of smaller power users, it seems unlikely that any technique could correctly pick out a channel estimate with sufficient SINR for the purposes of data decision-making. To overcome this problem, we now require to investigate, in more detail, the operation of blind signal parameter estimation techniques [28, 29]. Convergence of these algorithms is generally fast for small M and high SNR, and it degrades as either of these parameters alters significantly.

7 PERFORMANCE OF CDMA ARRAYS

The overall cellular system capacity in terms of users accommodated per cell for antenna array base stations has been analysed in a number of publications, including [4,26]. Two other authors have analysed base station schemes specific to CDMA systems [16,30]. More recently, analysis has been presented for IS-95 M-ary modulation systems [31]. In this section, the performance of a CDMA system, based on the eigenfilter method and a DPSK RAKE filter will be presented, using, as a quality measure, the mean BER for a given user. A single cell system will be considered to assess the number of active users who can be accommodated within the same RF bandwidth at acceptable multipath access interference levels.

The following assumptions have been made about the CDMA system:

- Each user is assumed to observe an $K = 4$ tap "slowly fading" channel with maximum Doppler frequency 0 Hz for each channel tap. The receiver is assumed to be able to perfectly track the desired user's channel.
- The CDMA interference is assumed to have a uniform distribution over the range of bearings [30°, 150°], Table 1.
- Each channel tap is corrupted by CDMA interference from all other users.

The performance of different antenna array sizes has been evaluated for $M = 1, 2, 4$ and 8 individual antenna elements. In each case, the maximum received signal value for a scattering width 2Δ has been calculated, assuming the source bearing is in the range [30°, 150°]. The results are shown for the desired user's BER vs total number of users in Figure 11.

The results demonstrate a significant performance improvement for a given number of users, by increasing the size of the antenna array. If a mean BER of 10^{-2} is taken as the threshold of acceptable performance, the capacity according to this measure increases from 30 users for 1 antenna to 189 for 8 antenna elements, Table 2, at a large mobile range.

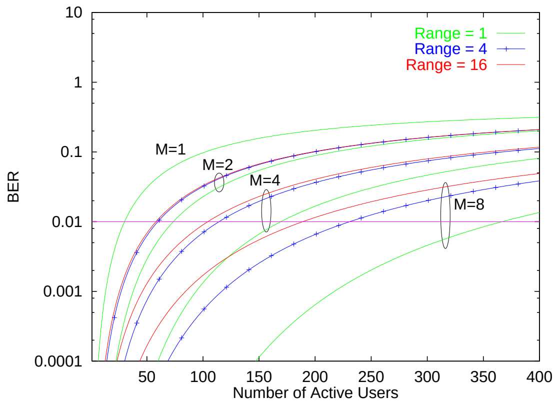

Figure 11 - Plot of error ratio against number of users in a 256 processing gain CDMA system for different numbers of antenna elements M and mobile ranges, as defined in Figure 5.

	Mobile Range		
M	1	4	16
1	30	30	30
2	73	59	58
4	169	114	105
8	366	230	189

Table 2 Maximum number of users for different M and mobile ranges for BER of 10^{-2}.

For cellular systems, with a uniform distribution of users throughout the network, an additional noise term of approximately 50 of the single cell CDMA interference is present. This effect will reduce the capacity by approximately one third however it can be compensated for by including error-correction coding and data interleaving [12]. In addition the system capacity may be doubled by using voice activity detection which only permits mobile transmissions when the user is speaking: typically, one person speaks during 40% of a telephone conversation. Table 2 summarises the performance improvement over several values of mobile range, Figure 5.

8 CONCLUSIONS

This paper has attempted to provide an introduction to the subject of antenna arrays for narrowband CDMA base station receivers. A number of points have been discussed, and are summarised below:

- Antenna arrays have been introduced to reduce cellular interference levels and improve capacity. Results in this paper suggest that employing M antennas can multiply the reverse link capacity by a factor of roughly M.
- Channel modelling aspects have been described: in urban areas, several channel taps are often resolvable.
- It has been shown that the significant channel taps or signals, observed at antenna arrays, may be modelled as the summation of array steering vectors. In urban areas, it is common for each vector entry to fade according to the Rayleigh distribution.
- The total angular spread at the basestation receiver is small for rural and urban environments but, in dense urban and indoor scenarios then the spread can exceed 180°.
- The 2D RAKE filter or space-time processor is clearly a promising and thoroughly investigated approach to releasing an effective CDMA antenna array receiver. Several algorithms have been considered [5,28,29] with the eigenfilter approach performing consistently well. As the angular width of the channel response increases, the receiver is able to exploit more spatial diversity.
- All the algorithms are known to degrade in the presence of high Doppler frequency signals, particularly when the angular spread from the users is large. This limits the performance or data rate for highly mobile users but, in indoor environments, or for walking pace dense urban users, then these algorithms do give the increase in performance to provide higher data rate services to these users.
- The BER performance of an antenna array receiver has been estimated and significant capacity increases have been demonstrated.

An important outstanding issue for antenna arrays is the scattering width of multipath components, Table 1. Values have been estimated for narrowband systems only. The interaction of the reverse and forward links is important in practical systems, particularly to ensure that the forward link can handle the increased traffic that antenna arrays can offer on the reverse link.

It should also be noted that smart antenna techniques are sometimes applied in TDMA mobile communications [31,32]. However, in these latter systems, the interfering users must be separated in space as these systems rely on the "space-division" multiple access concept which is somewhat distinct from the processor techniques discussed here.

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