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MULTI-BEAM ADAPTIVE BASE-STATION ANTENNAS FOR CELLULAR LAND MOBILE RADIO SYSTEMS

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ABSTRACT

This paper addresses the problem of meeting the proliferating demands for mobile telephony within the confinements of the limited radio spectrum allocated to these services. A multiple beam adaptive base-station antenna is proposed as a major system component in an attempt to solve this problem. This novel approach is demonstrated here by employing an antenna array to resolve the angular distribution of the mobile users as seen at the base-station site, and then using this information to direct beams towards the mobiles in both transmit and receive modes. The energy associated with each mobile is thus confined within the addressed volume, greatly reducing the amount of co-channel interference experienced from and by neighbouring co-channel cells. For a given performance criterion, this results in an increase in the spectral efficiency or capacity of the network.

1.0 INTRODUCTION

The frequency spectrum is, and always will be, a finite and scarce resource, thus there is a fundamental limit on the number of radio channels which can be made available to mobile telephony. Hence, it is essential that Cellular Land Mobile Radio (LMR) networks utilise the radio spectrum allocated to this facility efficiently, so that a service can be offered to as large a subscriber community as possible. Indeed, a major consideration of the second generation cellular discussions in both the US and Europe has focussed on this point. However, present and proposed future generation cellular communication networks which employ either omni-directional, or broad sector-beam, base-station antennas, will be beset with the problem of severe spectral congestion as the subscriber community continues to expand.

A measure often used to assess the efficiency of spectrum utilisation is the number of voice channels per MHz of available bandwidth per square kilometre [1]. This defines the amount of traffic that can be carried and is directly related to the ultimate capacity of the network. Hence, as traffic demands increase, the spectral efficiency of the network must also increase if the quality and availability of service is not to be degraded. At present this is overcome in areas with a high traffic density by employing a technique known as *cell splitting*. However, the continuing growth in traffic demands has meant that cell sizes have had to be reduced to a practical minimum in many city centres in order to maintain the quality of service. Unfortunately the number of subscribers able to simultaneously access these systems is still well below the long term service forecasts. This places great emphasis on maximising the spectral efficiency, or ultimate capacity, of future generation systems, and thereby fulfilling the earlier promises of performance. There has already been significant developments in terms of spectral efficient modulation schemes, eg. the US digital linear system [2][3] and the proposed 2nd generation Pan-European cellular network [4]. Also, in the area of antenna technology, the use of fixed coverage directional antennas has been considered [5]. In particular, the use of fixed phased array antennas, with carefully controlled amplitude tapers and sidelobe levels for the enhanced UK TACS network (ETACS) [6], are currently under evaluation. However, the use of *adaptive antenna arrays* has hitherto received little attention, especially in view of the rapid advances made in this field in military and satellite communications.

In this paper a multiple beam adaptive base-station antenna is proposed to complement other solutions, such as spectrum efficient modulation, currently being developed to meet the proliferating demands for enhanced capacity in cellular networks. The feasibility of such a scheme is demonstrated, and a comparison made with existing conventional antennas in a realistic mobile radio environment. Geometrical and statistical propagation models are used and a unique insight is given into the benefits of utilising adaptive base-station antennas in a cellular radio system. The concept of such a scheme is discussed and then demonstrated using results generated by a computer simulation of a simplified mobile scenario. The realisation of a fully adaptive base-station antenna test rig is then discussed.

2.0 ADAPTIVE ANTENNA ARRAYS

Adaptive antennas operate by exploiting some property of the signal environment present at the array aperture [7]. Classically they are defined as antennas that can modify their radiation pattern, frequency response, or other parameters, by means of internal feedback control while the antenna system is operating. The basic operation is usually described in terms of a receiving system steering a *null*, that is, a reduction in sensitivity in a certain angular direction, towards a source of interference. Following the pioneering work of Howells, Applebaum and Widrow [7][8] there has been considerable research activity in the field of adaptive antenna arrays, particularly for reducing the jamming vulnerability of military communication systems. However, to date, there has been little attention to the application of such techniques in the area of civil land mobile radio.

Multiple beam base-station antenna arrays have been considered by Davies *et al* [9] for enhancing the number of simultaneous users accessing future generation cellular networks. It is suggested that each mobile is tracked in azimuth by a narrow beam for both mobile-to-base and base-to-mobile transmissions. The directive nature of the beams ensures that in a given system the mean interference power experienced by any one user, due to other active mobiles, would be much less than that experienced using conventional wide coverage base-station antennas. It has already

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been stressed that high capacity cellular networks are designed to be interference limited, so, the adaptive antenna would considerably increase the potential user capacity.

The only study previous to the work discussed above considering the use of an adaptive antenna array in land mobile radio was Marcus and Das [10] in 1983. The analysis assumed that the base-station, or repeater, sites could be placed closer together if an antenna array formed 20dB nulls towards co-channel sites. This effectively reduces the amount of co-channel interference at the output of the base-station. It was suggested that in this system the beam steering information could be derived from the squelch tone injection which is presently used in the U.S. FM land mobile radio.

In contrast to the null steering technique considered by Marcus and Das, here the ability of the adaptive array to steer radiation pattern maxima towards the mobiles is considered. In the limit it can be envisaged that individual beams will be formed towards each mobile [9]. However, the integration of adaptive antenna array technology into an arbitrary communication system is not straightforward. At present, no one particular modulation scheme, or access technique, has been selected for the 3^{rd} generation of cellular systems, although some well established trends are becoming apparent in the quest towards more spectrally efficient modulation schemes [1] for the systems of the year 2000 and beyond. Hence it is vital during the initial stages of research to develop antenna architectures which are, in essence, modulation scheme independent.

3.0 Reduction of Co-Channel Interference using Adaptive Antennas

In this section the integration of an idealised adaptive array into an existing cellular network is considered. Only a summary of the analysis is presented here, the remainder forming the basis of another paper recently submitted for publication [11]. In order to ascertain the benefits of this class of antenna system, compared with that of conventional omni-directional base-station antenna systems, the following network topology has been assumed:

(a) A cellular network consisting of hexagonal cells, with channel reuse every C cells (C is the cluster size).
(b) The base-station transmitters are centrally located within each hexagonal cell.
(c) There is a *uniform distribution* of users per cell.
(d) There is a blocking probability of B in all cells.
(e) The omni-directional base-station antenna has an ideal beam pattern, giving a uniform circular coverage.
(f) The adaptive base-station antenna can generate any number, m, of ideal beams, with a beamwidth of $2\pi/m$, and a gain equal to the omni-antenna.
(g) Each adaptive beam will only carry the channels that are assigned to the mobiles within its coverage area.
(h) Any mobile (or group of mobiles) can be tracked by the adaptive base-station antenna.
(i) The necessary base-station hardware is available to enable beam-forming and tracking.
(j) The same modulation scheme can be used with each antenna system.

The blocking probability of B in assumption (d) is the fraction of attempted calls that cannot be allocated a channel. If there are 'a' *Erlangs* of traffic intensity offered, the actual traffic carried is equal to a(1 - B) Erlangs. The Erlang is a measure of traffic intensity , and measures the quantity of traffic on a channel or group of channels per unit time. This gives an *out-going channel usage efficiency* (or loading factor) [12] of

$$\eta = a(1 - B)/N \qquad (1)$$

where N is the total number of channels allocated per cell.

Assumptions (f), (g) and (h) imply the deployment of a somewhat hypothetical adaptive antenna system. This approach can be justified since a uniform user population has been assumed for both categories of antenna system. It is recognised that the dynamic, non uniform, user distribution will have a significant effect on the results presented here. This will be considered in a subsequent more rigorous study. Also, in the analysis which follows only the base-to-mobile link has been studied, however it can be shown that the analysis is also valid for the mobile-to-base link.

Two different categories of co-channel interference models were used as the basis for the study presented here. The first was the geometrical model adopted by Lee [5], followed by a more rigorous statistical analysis [12][13][14].

3.1 Geometrical Propagation Model

This approach considers the relative geometry of the transmitter and receiver locations, and takes into account the propagation path loss associated with the mobile radio channel.

3.1.1 One co-channel cell

Consider one co-channel cell which forms part of a cellular network as shown in figure 1. By definition both the cells have the same channel allocation, and a reuse distance of D separating the base-station transmitters. The *co-channel reuse ratio* is defined as

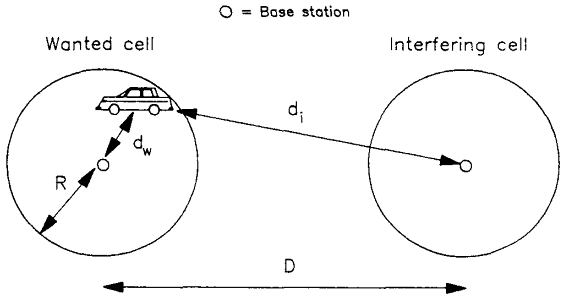

Figure 1: Two Co-channel Cells.

$$Q = D/R \qquad (2)$$

This ratio has also been termed the *co-channel interference reduction factor* [5] since the larger it is (ie. the further apart the cells) the less the co-channel interference. The level of acceptable co-channel interference governs the value of this parameter and the overall spectral efficiency of the network.

Co-channel interference will occur when the ratio of the received wanted signal envelope, s_w, to the interfering signal envelope, s_i, is less than some *protection ratio*, p_r, ie. when $s_w \le p_r s_i$. The protection ratio is defined by the modulation scheme employed [1]. Considering only the propagation path loss, the received signal envelopes are equal to the area mean signal levels at the mobiles, m_w and m_i. A commonly used approximation is that the received signal power is inversely proportional to the fourth power of the range [15]. Hence, the ratio of the received signal envelopes at the mobile (in volts) becomes

$$\frac{s_w}{s_i} = \frac{m_w}{m_i} = \frac{d_i^2}{d_w^2} \le p_r \qquad (3)$$

So, for a given protection ratio, a locus can be drawn which defines regions where co-channel interference will never occur (ie. around the wanted base-station) and where it has a high probability of occurring. This, in turn, determines the minimum spacing between co-channel cells in order to avoid interference. In the outer region the occurrence of co-channel interference is a statistical phenomena, hence it is necessary to introduce the concept of the *probability of co-channel interference* occurring, i.e. $P(s_w \le p_r s_i)$. This is often called the *Outage Probability*, and is the probability of failing to obtain satisfactory reception at the mobile in the presence of interference.

If the cells are considered to be identical, i.e. have equal blocking probabilities, then on average, there will be $N\eta$ active channels in each cell. So, in the case of the omni-directional antenna, given that the wanted mobile is already allocated a channel, the probability of that channel being active in an interfering cell is the outage probability.

Now consider the case of the adaptive antenna as previously described, with m beams per base-station providing coverage of the whole cell, and with $N\eta/m$ channels per beam, given a uniform distribution of users. The same regions of co-channel interference can be defined however, when the wanted mobile is within the region where co-channel interference may occur, the outage probability is reduced. The wanted mobile is *always covered* by at least one beam from the co-channel cell, hence the outage probability is equal to the probability that one of the channels in the aligned beam is the corresponding active co-channel[1] and is given by

$$P(s_w \le p_r s_i) = \frac{\text{channels per beam}}{\text{Total no. channels}} = \frac{N\eta/m}{N} = \frac{\eta}{m} \qquad (4)$$

where the omni- case is given by m = 1. It can be seen that the use of a multiple beam antenna reduces the outage probability in the region of interference by a factor m, corresponding to the number of beams formed.

3.1.2 Six Co-channel Cells

The previous approach can now be simply extended to assess the effect of six co-channel interferers, ie. the first tier of co-channel cells in a conventional cellular scheme. It is considered that further tiers of interferers will not significantly affect the results except when reuse distances become small. Again regions can be defined where co-channel interference will never occur and where it has a high probability of occurring. Since it is assumed that all m beams per cell are formed, there are six beams aligned onto the wanted mobile at any time. The outage probability within the region of interference is then found by considering the probability that the active co-channel is in each of these beams, ie.

$$P(s_w \le p_r s_I) = \left[\frac{\eta}{m}\right]^6 \qquad (5)$$

where s_I is the total co-channel interference.

3.1.3 Analysis of Results

The use of adaptive multiple beam-forming base-stations would, based upon the analysis presented so far, appear to give an improvement in performance with regard to the reduction of the probability of co-channel interference. The improvement depends on the degree of adaptivity used, ie. the number of ideal beams formed. However, the above approach is over simplistic and gives a rather optimistic view of the situation. Firstly, the beams are assumed to be ideal, giving an equal gain over the whole beamwidth. In practice this would not be the case. Also, a hypothetical situation could be envisaged where, if m is large enough to satisfy a given outage criterion[2], it would appear that the ultimate reuse distance (D/R = 2) is possible for any modulation scheme. Hence, adjacent cells are co-channel cells, the radius of which is decided by the required coverage area of the base-station site. In spite of this though, the analysis has been useful in introducing some of the important factors that affect the performance of a mobile radio network which exploits frequency reuse as a means of increasing spectral efficiency.

3.2 Statistical Propagation Model

There is seldom a line of sight path between the base-station and the mobile, and hence radio communication is obtained by means of diffraction and reflection of the transmitted energy. This produces a complicated signal pattern causing the field strength to vary greatly throughout the cell, and the received signal at the moving mobile to fluctuate very rapidly. This is generally attributed to the superposition of two different classifications of signal fading phenomenon. *Fast fading* (or just fading) due to the multipath nature of the received signal, and *slow fading* (shadowing), the slower variations of the received signal due to variations in the local terrain. In areas experiencing this type of signal variation, the area mean signal level is essentially constant. In order to model these propagation effects, they are included in a statistical fashion, the fading and shadowing described above being represented by Rayleigh and log-normal type distributions respectively.

3.2.1 One Co-channel Cell

Various studies have been undertaken to analyse co-channel interference originating from a single co-channel interfering cell in an attempt to characterise the mobile radio environment. In particular the rigorous analysis by French [13] has been adopted here. The Rayleigh fading and log-normal shadowing distributions are combined and an expression can be obtained for the outage probability, $P(s_w \le p_r s_i)$ experienced at the wanted mobile. This is for an omni-directional antenna and the full derivation is given in the referenced work [13].

1: The 'active co-channel' is the channel that has also been allocated to the wanted mobile.

2: If there are 10 beams (m=10) a 10% outage criterion could be satisfied in a fully loaded system.

With an adaptive antenna it is necessary to also consider the probability of there being an active co-channel in the beam aligned onto the wanted mobile. This is given in equation (4) and the resulting outage probability becomes

$$P(s_w \leq p_r s_i, m) = P(s_w \leq p_r s_i).(\eta/m) \qquad (6)$$

ie. the probability that the ratio of the wanted signal to the interfering signal is less than some protection ratio (as derived in [13]) and the probability that the aligned beam actually contains the active co-channel (equation (4)). Again it can be seen that the outage probability is reduced by a factor m. (Note again that the omni- case is given by m = 1)

3.2.2 Six Co-channel Cells

In order to present a more realistic comparison between omni-directional and adaptive base-station antennas, it is necessary to consider interference originating from multiple co-channel cells. Several different studies have pursued this goal, but of particular interest is the work by Muammar and Gupta [14]. This has been adopted here since the analysis follows directly from the previous discussion. It is recognised that there are many tiers of co-channel interferers present, but only the first, ie. cells at a distance D from the wanted base-station, is considered here. This assumption was shown to be valid in similar studies.

In order to calculate the total probability of co-channel interference (the outage probability), it is necessary to consider the probability of there being co-channel interference and n interfering co-channel cells. Using conditional probability theory this can be expressed as

$$P(s_w \leq p_r s_I) = \sum_n P(s_w \leq p_r s_I/n).P(n) \qquad (7)$$

$P(s_w \leq p_r s_I/n)$ is the *conditional outage probability* (the probability of co-channel interference given that there are n active interfering cells) and P(n) is the probability density function of n. Here only the first tier is considered, so the maximum number for n is six. Muammar and Gupta derived the expression for the conditional outage probability [14] and the resulting integral was solved numerically.

The probability density function of n, P(n), is given by the *origination probability* [12] and is the probability that n interfering co-channel cells are using the same channel as the wanted mobile. This has the form of a binomial pdf. In order to integrate the adaptive antenna, it is necessary to consider the probability that the interfering co-channel is in the beams pointing at the wanted mobile (equation 4). Since it is assumed that at any time all m beams per cell are formed, there will always be six beams aligned onto the wanted mobile. Hence the overall outage probability can be expressed as

$$P(s_w \leq p_r s_I, m) = \sum_n P(s_w \leq p_r s_I/n) \begin{pmatrix} 6 \\ n \end{pmatrix} \left(\frac{\eta}{m}\right)^n \left(1-\frac{\eta}{m}\right)^{6-n} \qquad (8)$$

where the omni-directional case is given for m = 1.

3.2.3 Spectral Efficiency

To gain a more meaningful interpretation when comparing different system architectures in a cellular network, the spectral efficiency [1] of the various schemes can be considered. This gives an unbiased measure of spectrum utilisation, and can be expressed as the number of channels per MHz of bandwidth per km^2, ie.

$$\text{Efficiency, } E = \frac{B_t/B_c}{B_t(CA)} = \frac{1}{B_c CA} \qquad (9)$$

where, B_t = Total available bandwidth.
B_c = Channel spacing in MHz.
C = Number of cells per cluster.
A = Cell area (km^2).

To enable a simple comparison to be made between omni- and adaptive antenna systems, it is necessary to assume that an identical modulation scheme will be employed in both cases. Thus $E \propto 1/C$, and the relative spectral efficiency can be expressed as

$$\frac{E_{adapt}}{E_{omni}} = \frac{C_{omni}}{C_{adapt}} \qquad (10)$$

Equations (6) and (8) above were solved numerically. A fading and shadowing (6dB variation) environment was considered, and the reuse distance Q and the cluster size C were calculated for a given outage probability criterion, protection ratio and loading factor. Then, using equation (10), the relationship between the relative spectral efficiencies was calculated as a function of the number of beams formed, and is shown in figure 2 for one and six co-channel interferers. Here an outage of only 1% was considered and, although this value is quite low, it serves to give some idea of the advantages that can be obtained by using this new

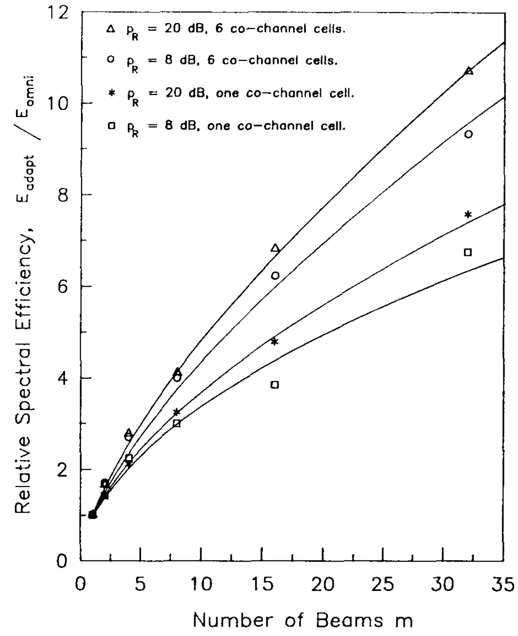

Figure 2: Relative Spectral Efficiency as a Function of the Number of Beams Formed.

class of base-station antenna. Two values of protection ratio, 8 dB and 20 dB, were considered in order to cover a variety of modulation schemes [1].

It can be seen from figure 2 that for a given outage criterion and modulation scheme, the introduction of adaptive antennas into an existing network, could produce at least a three-fold increase in efficiency for an eight beam antenna system. This can be equated to be three times the number of channels per MHz per kilometre^2, or simply as three times as many users in each cell.

4.0 The 'Smart' Antenna Concept

Adaptive antennas operate by exploiting some property of the signal environment present at the array aperture [7][8], and it is due to this ability that they are often aptly referred to as 'smart' arrays [16]. In the previous theoretical analysis it was assumed that the base-station antenna could track any mobile, or group of mobiles, within its coverage area. Therefore, on reception, the array must be capable of resolving the angular distribution of the users as they appear at the base-station site. Armed with this knowledge, the base-station is then in a position to form an optimal set of beams, confining the energy directed at a given mobile within a finite volume. This concept can be further illustrated by considering the sequence of events illustrated in figure 3. The scenario depicted is realistic of many operational systems where there are lone mobiles, or groups of mobiles, dispersed throughout the cell. Using the spatial distribution of the users acquired by the array on reception, the antenna system can dynamically assign single narrow beams to illuminate the lone mobiles, and broad beams to the numerous groupings along the major highways. It can be seen that by constraining the energy transmitted towards the mobiles, there are directions in which little or no signal is radiated. This reduces the possibility of co-channel interference in neighbouring cells, and thereby increases the spectral efficiency, or capacity, of the network as illustrated in the previous section.

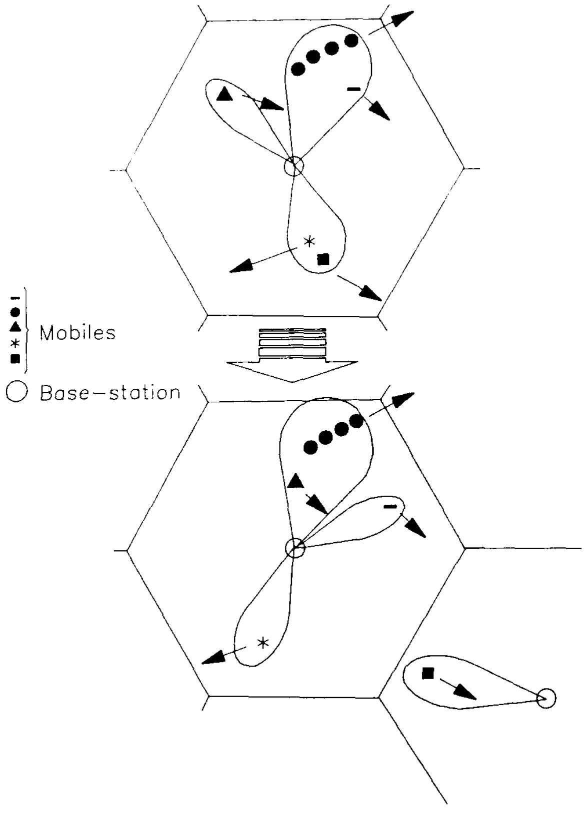

Figure 3: Optimal Beamforming.

The realisation of such an adaptive base-station antenna requires an architecture capable of locating and tracking the mobiles, and a beam-forming network thus capable of producing the appropriate multiple independent beams. The former requirement can be broadly classified as that of a direction finding, or a spatial estimation problem. These two tasks are illustrated in figure 4 as a source estimation or direction finding (DF) processor and a beamformer.

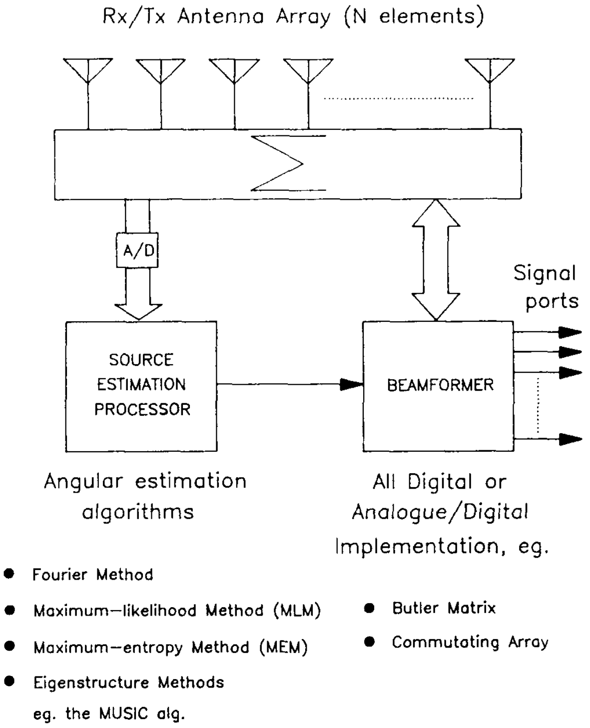

Figure 4: The 'Smart' Antenna Array.

4.1 Direction Finding

The classical problem in many radar, sonar and seismic applications is to utilise the multiple sensors in an antenna array to estimate the location of one or more sources of signal energy, ie. *direction finding* (DF), and to track their movements. The traditional method used is often termed the Fourier Method and is mathematically equivalent to estimating the spatial Fourier Transform of the radiation field, and determining the location of local maxima. The disadvantage of this technique is that the resolution of two or more sources is restricted by the physical size of the array, and so the estimation accuracy can only be improved by increasing the array aperture. This solution has only a limited use since it requires increasing the physical size of the array. For this and other technical reasons modern DF systems tend to employ high resolution, or 'superresolution', techniques eg. the Maximum-Likelihood Method, MLM [17][18], the Maximum-Entropy Method, MEM [17] and the many Eigenstructure techniques, eg. the MUSIC algorithm [19].

Numerous authors have made comparisons between these fundamental angular estimation techniques in a multiple signal environment. However, their utilisation in a mobile communication environment has yet to be fully appraised. The performance of these techniques has been well documented, but the operational scenarios used in the simulations are limited especially in the context of the application in mind. The number of sources that it is necessary to resolve and track is far larger than anything so far considered. Also, the sources are unevenly distributed throughout 360° around the adaptive base-station antenna, and are constantly on the move. Although the source estimation algorithms will not have to resolve and track fast moving jet planes, as is usual in radar applications, they will have to operate in a highly dynamic and crowded environment. Therefore it is vital that their performance is initially evaluated with the use of computer simulations. Typical mobile scenarios can then be emulated and the various direction finding algorithms rigorously evaluated. (See section 5.0)

4.2 Beamforming

The basic requirement is a beamforming processor which can generate and assign an optimal set of beams to track the mobiles within the coverage area of the base-station. Decision making is based on *a priori* knowledge of the mobile distribution, obtained from the DF processor. The criterion for assigning beams is to minimise the number of directions in which signal energy is transmitted, thereby reducing the amount of co-channel interference.

Various beamforming techniques are currently being assessed, notably the use of a Butler Matrix [20] and a commutating array. Davies *et al* [9] proposed the use of a multiple commutating beam antenna which produces M fixed beams. This could be implemented by adapting a lens fed single commutating beam antenna array from single to multiple beam operation. Modifying the type of lens feed was suggested. Since complete channel reuse in each beam was propounded, many user transmissions would have to be multiplexed onto each fixed beam. Although a solution to this problem was not discussed, it was recognised that it would represent a significant problem.

However, the above techniques are not fully adaptive, such as that required to implement the system depicted in figure 3. The beams are of a finite width and number, as well as being in fixed directions. Hence, it would not be possible to track a lone mobile with a single beam. At present it is envisaged that the signal would be stepped from beam to beam as the mobile traverses the cell.

5.0 SIMULATION STUDY

The purpose of initial computer simulations is to allow development and evaluation of the concepts discussed above. A signal and noise environment is set up to simulate a number of sources (mobiles) distributed around the adaptive base-station antenna. To simplify matters, all sources are initially represented by plane waves with the same carrier frequency. Hence, together with the knowledge of the array configuration, it is possible to generate the signal vector that would be observed across the array aperture as well as the associated spatial correlation matrix. Contained within this matrix is all the essential geometrical information about the signal environment required by the DF algorithm to locate the mobiles.

Figures 5 and 6 show typical plots of the mobile distribution throughout a 180° sector of the cell, as a function of time. (Note that only the azimuth information associated with each source is used at this stage.) The mobiles follow predefined routes and the DF algorithm estimates their positions. In this example a uniform 8 element linear array with an element spacing of half a wavelength is simulated. At time $t = 0$ signals are arriving from directions -60°, -30°, 0° and 30° off boresight. The element signal-to-noise ratio is 0dB, the noise being modelled as additive white gaussian noise (AWGN), which may be due to disturbances sensed along with the signals as

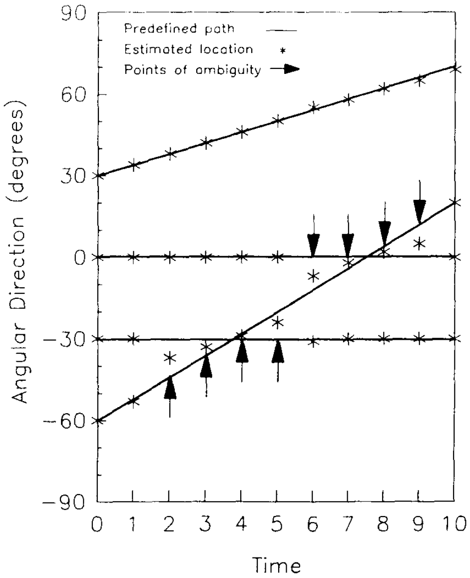

Figure 5: Estimation of Four Moving Sources Using the Fourier Method of DF.

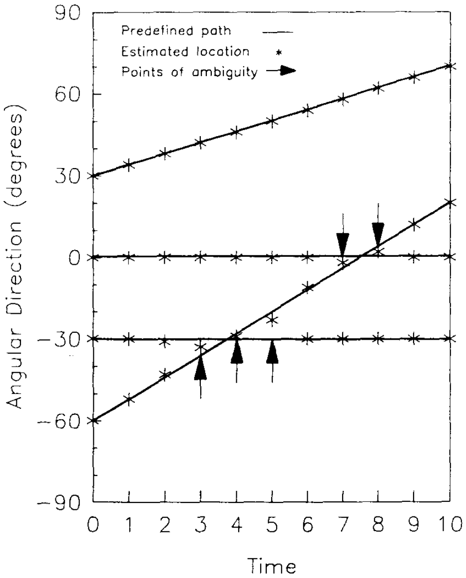

Figure 6: Estimation of Four Moving Sources Using the ML Method of DF.

well as internally generated 'thermal' noise in each channel. As yet, no attempt has been made to incorporate a propagation model of a typical mobile communications environment (see section 3.2). The sources have been assumed to be completely uncorrelated from element to element across the array. This can be shown [15] to be a valid initial assumption with an element spacing of at least $\lambda/2$ in a fading environment.

In figure 5 the DF algorithm used is the simple Fourier Method. Note the lack of available detail and poor resolution, especially as the sources move into close proximity. In figure 6 the MLM has been employed with a marked improvement in the ability of the array to resolve the mobiles. In this case the adaptive array weights are optimised to only pass signals from the directions of arrival (DOA's) of the mobiles [17][18].

Further techniques such as the Burg Maximum Entropy Method (MEM) and the Schmidt MUSIC algorithm need to be also assessed, as well as some of the more recent approaches [21]. The choice of algorithm will depend on various parameters, eg. the speed of response, the computational intensity and the ability to resolve multiple sources in a typical mobile environment. Once armed with the knowledge of the user distribution throughout the cell, the base-station is then in a position to optimally assign beams for the efficient transmission and reception of signals with each mobile.

So far nothing has been said about how such an antenna could be incorporated into an existing cellular network. Although it has been stressed that the proposal is designed to be essentially modulation scheme independent, it is recognised that many extra overheads would be incurred. For example, once calls are set up in the conventional way, how would the DF processor track the movements of every mobile and be able to identify each one individually ? Would it have to monitor each channel assigned to the mobiles separately, or could a single channel be used by all mobiles in order to fix their position ? Also, are these requirements necessary ? These and many other implementation problems have yet to be fully assessed, but with the use of further extensive computer simulations a much clearer insight will be obtained. However, at this conceptual stage, the prospects for such a base-station antenna are promising.

6.0 FUTURE WORK

It has already been stressed that further simulation work is required to fully appreciate how an adaptive base-station antenna could be implemented. Ultimately, however, the aim is for a 'smart' antenna test rig to allow a full and extensive evaluation of the proposed base-station architecture. Work is currently underway towards the construction of a 4 and 8 element patch antenna array (to operate between 1.5 and 1.7 GHz) and the associated receiver hardware. A four beam Butler Matrix beamformer is also being built, and it will serve to initially demonstrate the principles of operation. The choice of processor to implement the DF algorithm and optimal beamforming has yet to be made, although various possibilities are currently being evaluated. The software required for each process is being developed in conjunction with the simulation suite.

7.0 CONCLUDING REMARKS

The full potential of adaptive antenna technology in the future generation of ubiquitous portable communication networks is yet to be realised. The goal is to be able to provide universal pocket sized communications by the year 2000. This implies that the system must make very efficient use of the radio spectrum if it is to be made available to a large consumer base; thus making the portable equipment relatively cheap. Also, it is highly desirable that the portable communicator has a long duty cycle between battery recharging implying power efficient modulation. The role of adaptive antennas has already been discussed in terms of the former requirement, however, it must be emphasised that spectrum efficient modulation is still a vital parameter in the design of these systems. The potential enhancement of power efficiency obtainable using spatial filtering has not been fully assessed to date. The merits of this technique in a rural service area are of particular interest.

The study presented here has demonstrated the feasibility of an adaptive base-station antenna for cellular communications networks. A comparison made between the conventional and proposed schemes has shown that a marked improvement in spectral efficiency and capacity can be obtained. The concept has then been developed and a proposal put forward for a fully adaptive antenna test rig to demonstrate the principles of operation and show how such a scheme could be incorporated into the existing cellular framework.

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References

[1]: H. Hammuda, J.P. McGeehan and A. Bateman, *Spectral Efficiency of Cellular Land Mobile Radio Systems*, 38th IEEE Veh. Technol. Conference, 15-17th June 1988, Philadelphia, USA, pp 616-622.

[2]: J.A. Tarallo and G.I. Zysman, *Modulation Techniques for Digital Cellular Systems*, ibid, pp 245-248.

[3]: J. Uddenfeldt, K. Raith and B. Hedberg, *Digital Technologies in Cellular Radio*, ibid, pp 516-519.

[4]: F. Lindell, J. Swerup and J. Uddenfeldt, *Digital Cellular Radio for the Future*, The Ericsson Review, No.3, 1987.

[5]: W.C.Y. Lee, *Elements of Cellular Mobile Radio Systems*, IEEE Trans. Veh. Technol., Vol.VT-35, No.2, May 1986, pp 48-56.

[6]: P.C. Carlier, *Antennas for Cellular Phones*, Communications International, December 1987, pp 43-46.

[7]: S.P. Applebaum, *Adaptive arrays*, IEEE Trans. Ant. and Prop., Vol.AP-24, No.5, Sept. 1976, pp 585-598.

[8]: B. Widrow, P.E. Mantey, L.J. Griffiths and B.B. Goode, *Adaptive antenna systems,* Proceedings of IEEE, Vol.55, No.12, Dec. 1967, pp 2143-2159.

[9]: W.S Davies, R.J. Lang and E. Vinnal, *The Challenge of Advanced Base-station Antennas for Future Cellular Radio Systems*, IEEE International Workshop - Digital Mobile Radio, Melbourne, Australia, 10th March 1987.

[10]: M.J. Marcus and S. Das, *The Potential use of Adaptive Antennas to Increase Land Mobile Frequency Reuse*, IEE 2nd International Conference on Radio Spectrum Conservation Techniques, 6th- 8th Sept. 1983, CP224, Birmingham, UK.

[11]: M.A. Beach, S.C. Swales, D.J Edwards, *Multi-beam Adaptive Base-station Antennas for Future Cellular Land Mobile Radio Systems*, submitted for publication in IEEE Trans. on Veh. Technol.

[12]: K. Daikoku and H. Ohdate, *Optimal channel reuse in cellular land mobile radio systems,* IEEE Trans. Veh. Technol., Vol.VT-32, No.3, pp 217-224, Aug. 1983.

[13]: R.C. French, *The effects of fading and shadowing on channel reuse in mobile radio,* IEEE Trans. Veh. Technol., Vol.VT-28, No.3, pp 171-181, Aug. 1979.

[14]: R. Muammar and S. Gupta, *Co-channel interference in high capacity mobile radio systems,* IEEE Trans. Comms., vol. COM-30, No. 8, pp 1973-1978, Aug. 1982.

[15]: W.C. Jakes, *Microwave Mobile Communications*, John Wiley & Son, USA, 1974, ISBN 0-471-43720-4.

[16]: W.F.Gabriel, *Adaptive Arrays - An Introduction,* IEEE Proceedings, Vol.64, No.2, Feb 1976, pp 239-272.

[17]: W.F.Gabriel, *Spectral analysis and adaptive array superresolution techniques,* IEEE Proceedings, Vol.68, No.6, June 1980, pp 654-666.

[18]: Don H. Johnson, *The application of spectral estimation methods to bearing estimation problems,* IEEE Proc., Vol.70, No.9, Sept. 1982, pp 1018-1028.

[19]: R.O. Schmidt, *Multiple emitter location and signal parameter estimation,* IEEE Trans. Ant. and Prop., Vol.AP-34, No.3, March 1986, pp 276-280.

[20]: W.F. Gabriel, *Estimation techniques in adaptive processing antenna systems,* IEEE Trans. Ant. and Prop., Vol.AP-34, No.3, March 1986, pp 291-300.

[21]: H.M. Bayri, D.R. Ucci and C.C Yeh, *Improved Bearing Estimation of Signals in the Presence of Unknown Coloured Noise,* ICC 1987, pp 1028-1031.