

An Overview of Space Division Multiple Access Techniques in Cellular Systems

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Abstract: This paper provides an overview of the basic principles of Smart Antenna techniques as applied to the introduction of Space Division Multiple Access (SDMA) techniques in current mobile radio networks, as well as in Personal Communication Services (PCS), Personal Communications Networks (PCN) and the Universal Mobile Telecommunication System (UMTS). It is shown qualitatively how SDMA techniques can increase the capacity of cellular network. Furthermore, a new SDMA principle based on the non-homogeneous Quality of Service requirements in mobile multi-media networks is introduced with application to systems proposed for UMTS.

I. INTRODUCTION

Faced with the rapid increase in mobile subscribers in the last years, cellular network operators and service providers have been forced to optimize and upgrade their networks on a continuous basis in order to ensure that subscribers are guaranteed adequate coverage and signal quality. For example, in Japan users of mobile communication systems, including cellular and cordless, have increased dramatically at the rate of more than one million new users per month. With spectrum being an extremely expensive commodity, operators are looking to equipment manufacturers to supply innovative solutions to enable them to optimally use their allocated resources. In addition to the rapid uptake of voice services, users of mobile telephony are increasingly showing an interest in the availability of more advanced data and multi-media services via mobile networks, sparking such initiatives such as UMTS.

This path of rapid evolution has brought with it some of the biggest engineering challenges to date. A couple of years ago, the design of a communication system capable of operating in multiple propagation environments, delivering a broad range of services each with its own quality requirements on a

global scale to a person with a single handheld terminal [1] would have sounded far fetched. Today this is reality. The European Telecommunication Standards Institute (ETSI) have recently decided to adopt Wideband Code Division Multiple Access (W-CDMA) and Time-Division CDMA (TD-CDMA) as basis for the implementation of UMTS, opening the way for the standardization process to be completed and for the introduction of advanced mobile service to commence. What is of specific interest in the W-CDMA and TD-CDMA proposals is that the use of smart antenna and SDMA [2], [3], [4] concepts are fully supported by the standard in order to increase the capacity of third generation mobile systems. Specifically, SDMA techniques will be implemented to yield

Increased cell coverage areas to reduce high base station site cost in low traffic areas.

Reduction of interference to improve service quality and/or increase the frequency re-use factor. This point is especially important in CDMA based systems which are interference limited.

Extend system traffic capacity.

In the following section, the operating principle of smart antennas and SDMA systems will be discussed and it will be shown qualitatively how these

techniques increase the performance of cellular systems. Since adaptive antennas forms the basis of the smart antenna principle, Section III presents an overview of the basic operation of adaptive antennas. Section IV will highlight the aspects that influence the efficiency of the smart antenna and SDMA techniques discussed in Section II and present an example of how smart antenna techniques may be applied to TD-CDMA systems. Finally, conclusions are presented in Section V.

II. SMART ANTENNAS AND SDMA

Cellular access systems rely on the fact that users of a single resource - the Base Station (BS) - will be separable in one or more domain, that is frequency (viz FDMA), time (viz TDMA) or code (viz CDMA). Thus, in a FDMA system (for example AMPS [5] and CT-2 [6]), simultaneous transmissions to a BS will have different carrier frequencies and will therefore not interfere with one another. Similarly, in a TDMA system (for example the access method employed in one frequency allocation in an IS-54 system [6]), transmissions to the BS are separated in time to prevent interference. These multiple access techniques can also be combined to form, for example, TDMA/FDMA (IS-54) or FDMA/CDMA (IS-95 [6]) systems or any combination thereof. All of the above mentioned multiple access techniques do however share one common trait, being the non-homogeneous geographical distribution of their subscribers. This means that all of the mentioned multiple access systems can exploit another dimension, viz the spatial dimension, of the cellular problem to increase system capacity or cellular spectral efficiency.

In [7], cellular spectral efficiency is defined as a basis to rate the performance of a cellular system. Many definitions for cellular spectral efficiency have been proposed, including *bit/s/Hz* (with the data rate measured as some predefined Bit Error Rate (BER)), *Erlang/MHz/km²*, equivalent telephone Erlangs per square kilometer [8] and even Mbit/s-per-floor for indoor environments [8]. Because SDMA and smart antenna systems rely on spatial parameters, a spatial parameter is included in the definition of spectral efficiency in order to evaluate cellular system performance:

Definition 1: Cellular Spectral Efficiency (η)

The cellular spectral efficiency of a system is defined as the sum of the maximum data rates that can be delivered to subscribers affiliated to all base stations in a re-use cluster of cells, occupying a defined physical area.

Mathematically, cellular spectral efficiency, η is defined as

$$\eta = \frac{\sum_{j=1}^r \sum_{i=1}^K R_{ij}}{B} \frac{1}{A_{cluster}} \quad \text{bit/s/Hz/km}^2 \quad (1)$$

where r denotes the number of cells in a re-use cluster, R_{ij} denotes the data rate measured in *bits/s* at some predefined BER available to subscriber i in cell j of the re-use cluster, B denotes the total bandwidth measured in *Hz* allocated to all cells in the re-use cluster and $A_{cluster}$ denotes the physical area, measured in *km²*, occupied by the re-use cluster. Clearly, the concept of the re-use cluster is fundamental in the determination of η . Definitions for a re-use cluster can be found in [9]. In this paper, a re-use cluster will be defined as follows:

Definition 2: Re-use Cluster (r)

A set of cells which have access to the total Time/Frequency and Code (T/F/C) resources available in the cellular system.

Figure 1 shows this scenario, for the case where $r = 3$. Thus, each set of cells forming a re-use pattern exists totally independent (as far as T/F/C resources go) of the other cells in the area.

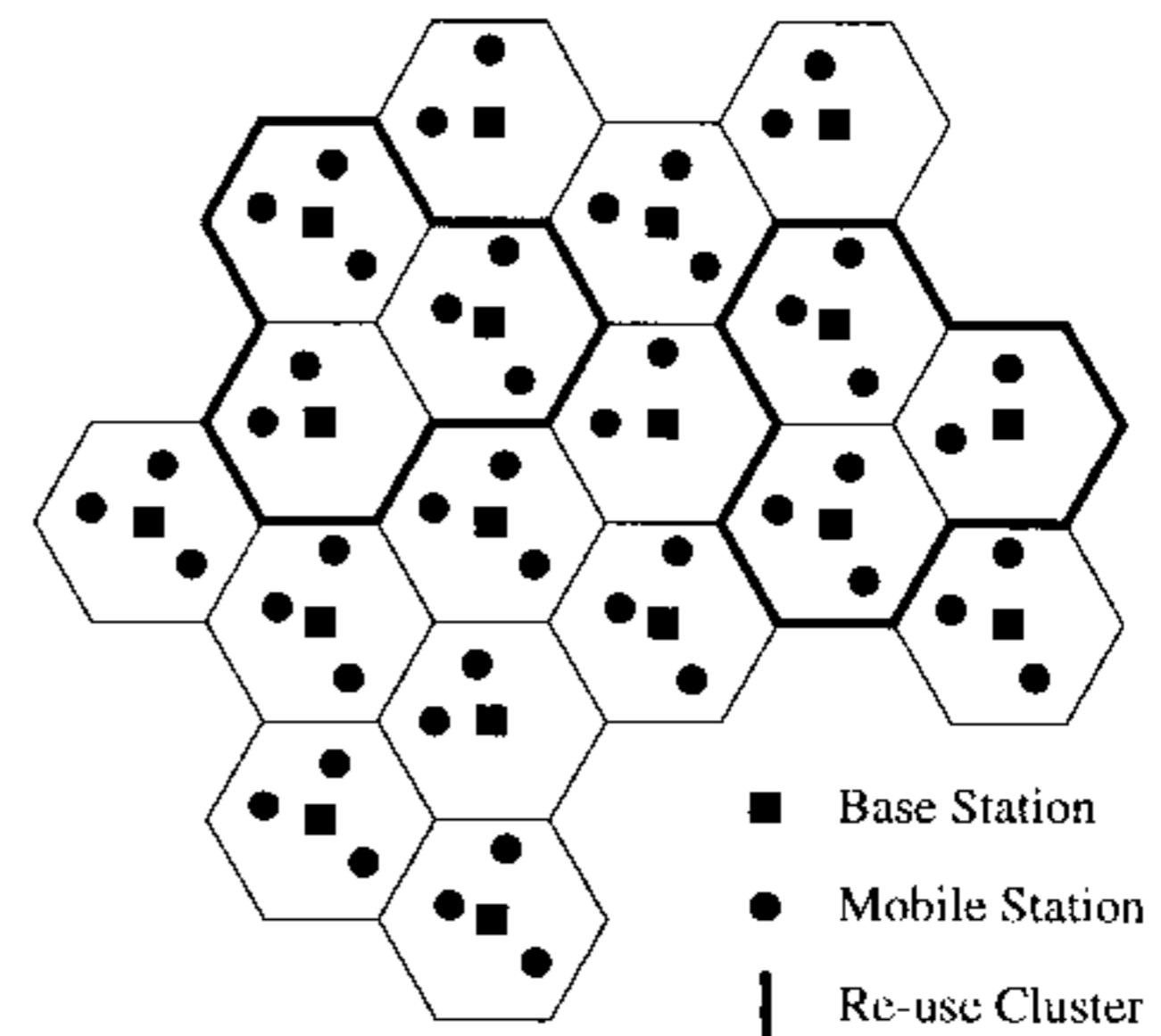


Fig. 1. Cellular re-use concept.

With the above definitions in mind, the task of a smart antenna or SDMA system is clear - optimize the cellular spectral efficiency of the network, or in other words, increase the re-use of the available cellular resources. Examining (1) it is clear that reducing the size of the re-use cluster will increase the cellular spectral efficiency. However, a reduced cell size will significantly increase the interference presence in the cell limiting the capacity of the network in the case of a CDMA system. The increased amount of interference, specifically in the uplink, can be overcome using a smart antenna technique

called High Sensitivity Reception (HSR).

Definition 3: High Sensitivity Reception

High Sensitivity Reception refers to the use of adaptive antenna arrays in the uplink of a cellular network to focus the antenna beam on a specific user, thereby increasing the antenna gain in the direction of the user and suppressing transmissions received from interfering users.

This concept is depicted in Figure 2. In the case of TDMA and FDMA systems the HSR system may use pencil antenna beams [10] to focus on the active users whereas in CDMA systems, the HSR system can increase the signal-to-noise ratio (SNR) in the uplink by introducing nulls in the antenna pattern in the direction of strong interfering signals. The antenna gain of HSR with an M -element antenna is equal to $10 \log M$, where M is the number of elements in the array.

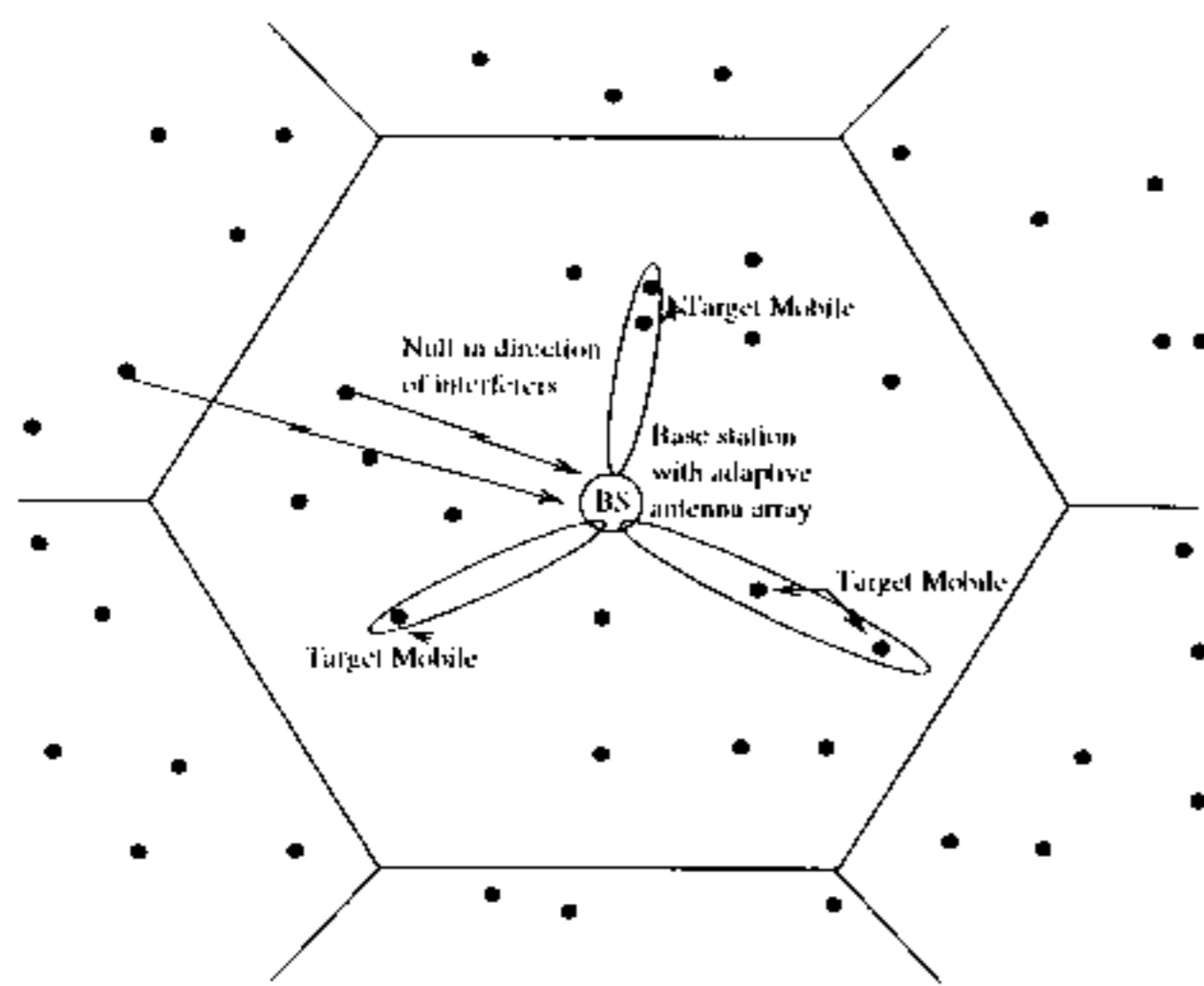


Fig. 2. SDMA system implemented using adaptive antenna arrays.

In a manner similar to HSR, Spatial Filtering for Interference Reduction (SFIR) can be used in the downlink of a cellular system to focus all the energy radiated by the base station onto a single user or cluster of users. Therefore, SFIR is defined as:

Definition 4: Spatial Filtering for Interference Reduction

SFIR reduces the interference experienced by mobile communication systems in the downlink by concentrating all radiated electromagnetic energy in the direction of a user or group of users, avoiding geographical areas where no users are active.

Because the uplink of a cellular network is in general the capacity limiting factor, it might seem that HSR systems will yield greater capacity advantages than SFIR systems. However, the increased downlink quality afforded by SFIR techniques may lead to less dropped calls during handovers (because of the better signal quality estimates available to the

mobile), increasing the overall quality of service. Also, due to the dynamic nature of an adaptive antenna array, a SFIR system can facilitate the tracking of a user across cell boundaries, increasing the chances of a successful handover to the next cell.

Whereas HSR and SFIR techniques increase the cellular spectral efficiency by decreasing the total co-channel interference levels in a cell, SDMA techniques increase cellular spectral efficiency by decreasing $A_{cluster}$ with the consequent decreasing in the physical size of the re-use cluster. In other words, the same physical cellular network resources can be re-used more often. Various definitions have been proposed to define SDMA techniques [2], [4], [3]. We summarize these as follows:

Definition 5: Space Division Multiple Access

A SDMA system is a multiple access technique which enables two or more subscribers, affiliated to the same base station, to use the same Time and Frequency and Code (T/F/C) resources on the grounds of their physical location or spatial separation.

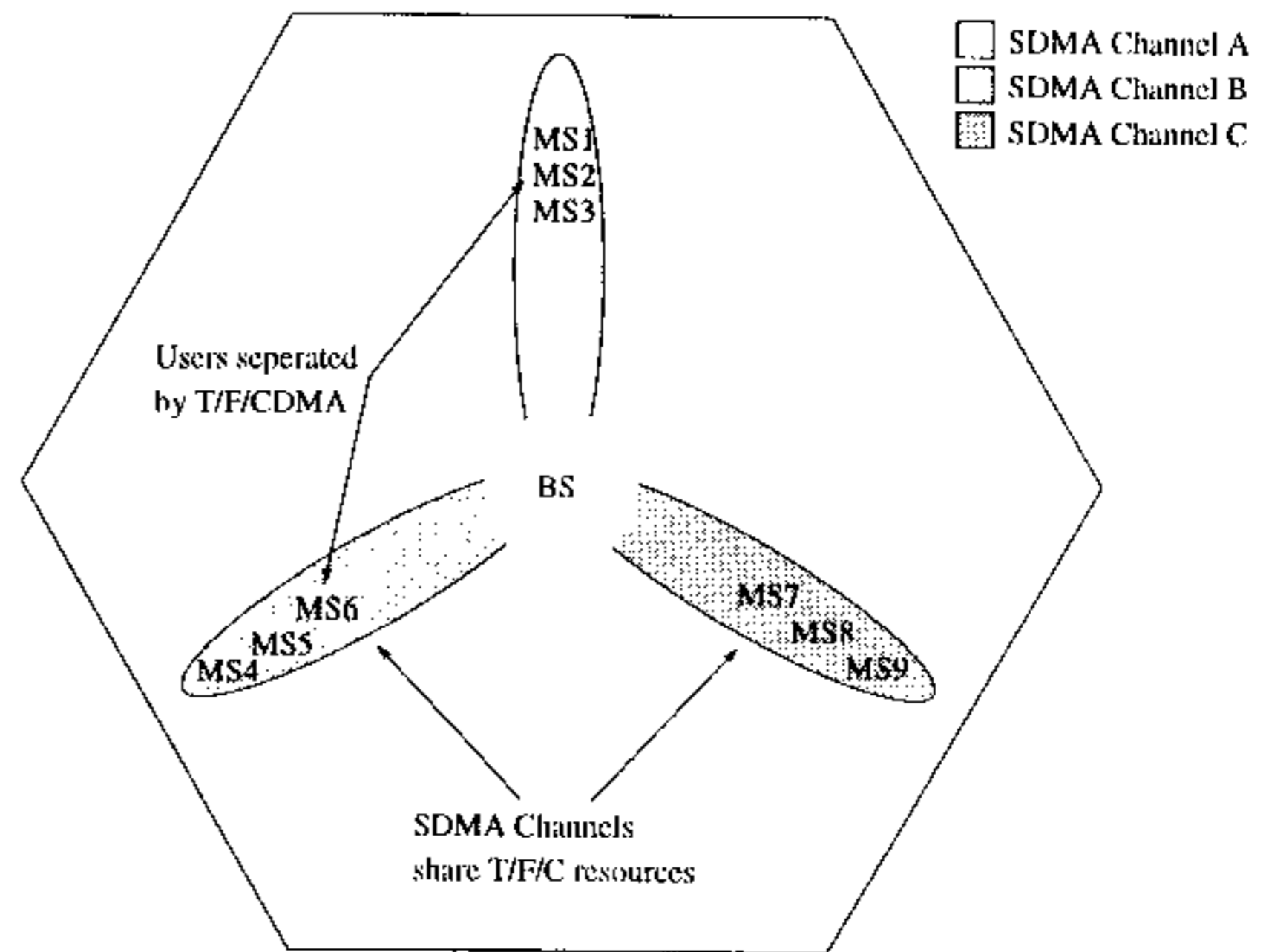


Fig. 3. Space Division Multiple Access (SDMA): Allowing users in the same cell to share time/frequency and code resources.

This scenario is depicted in Figure 3, where Mobile Stations (MS) MS1, MS2 and MS3 share a same set of T/F/C resources with MS4, MS5, MS6 and MS7, MS8 and MS9. For example, MS4 and MS1 may both be allocated carrier frequency f_1 , time slot T_1 and code c_1 although they are affiliated to the same BS, because of their spatial separation. It has been shown analytically and by measurements that gains in the order of 5-9 dB can be obtained using antenna arrays with 8 elements.

The overall system gains that can be achieved with the techniques described above, depend heavily on the type of cellular structure employed. A plethora of different cellular structures have been defined in the literature [11], [12], [13], [14], [15], [8]. Amongst these, the best known are microcells, macrocells, picocells and umbrella cells, defined as follows:

Definition 6: Microcell

A microcell is a relatively small cell (0.4-2 km diameter) with base station antenna(s) situated below the local urban skyline, and utilizing relatively low levels of transmitter power (around 20 mW) with rms delay spreads in the order of 10 to 100 ns [16]. Typically, microcells are employed in three areas [12]:

1. *Hot Spots*: Service areas with high teletraffic densities, or areas with poor coverage.
2. *Downtown Clustered Microcells*: Urban maze of street canyons - serves pedestrians and mobiles.
3. *In-Building*: Indoor cells to serve eg. an open plan office where users have limited mobility.

Definition 7: Macrocell

A macro cell is a relatively large cell (2-20 km diameter) with base station antennas situated well above the local urban skyline, and utilizing large levels of transmitted power (around 0.6-10 W) with rms delay spreads in the order of 0.1 to 10 μ s [16].

Definition 8: Picocell

A picocell is a small cell (less than 0.4 km in diameter) with base station antennas situated at ceiling level and using very little transmitter power (0.01-0.1 W).

Picocells are typically employed inside buildings or in areas with an extremely high traffic density.

Definition 9: Umbrella cell

An umbrella cell covers the same geographical area as a number of micro- or picocells, and are aimed at supplying service to subscribers with high mobility in these areas.

The relationship of the above mentioned cells are shown in Figure 4. In a fully operational cellular environment, such as that envisioned in UMTS, all the mentioned cellular structures will be present and will work together to provide seamless service, irrespective of the subscriber's physical location or mobility [17].

In a given cellular structure adaptive antennas are needed to realise the smart antenna concept. The adaptation of the antenna pattern can be ac-

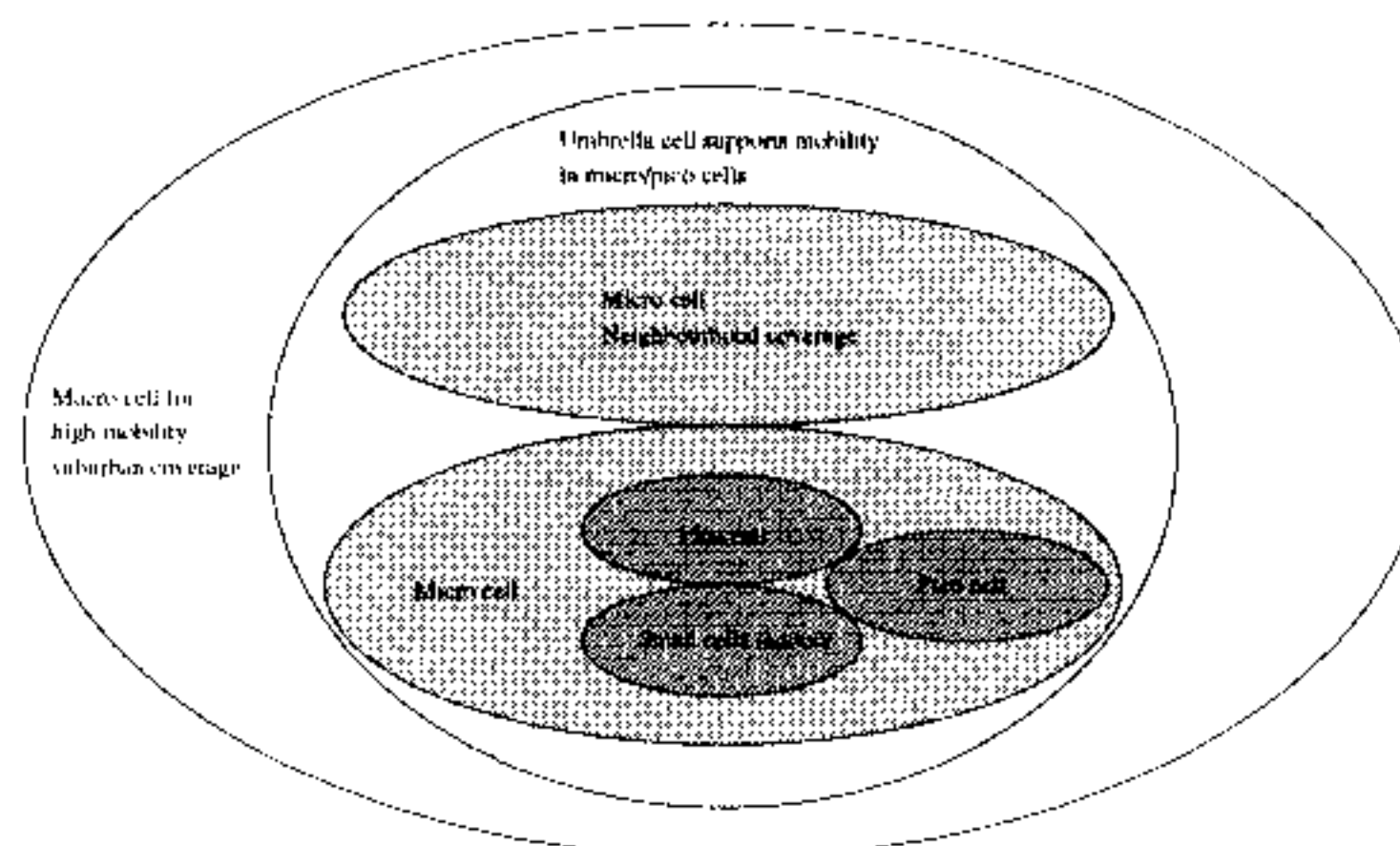


Fig. 4. Micro, macro, pico and umbrella cells work together to provide seamless service.

complished with adaptive antenna arrays or an adaptive beam formers [18], [19], [20]. An adaptive antenna array for use in a SDMA environment is defined as follows:

Definition 10: Adaptive Antenna Array

An adaptive array consists of an array of spatially distributed radiating elements, with each element in the array receiving highly correlated replicas of the signal, where the outputs of each element is adaptively weighted and combined with the other outputs to extract a specific signal from the superposition of signals received.

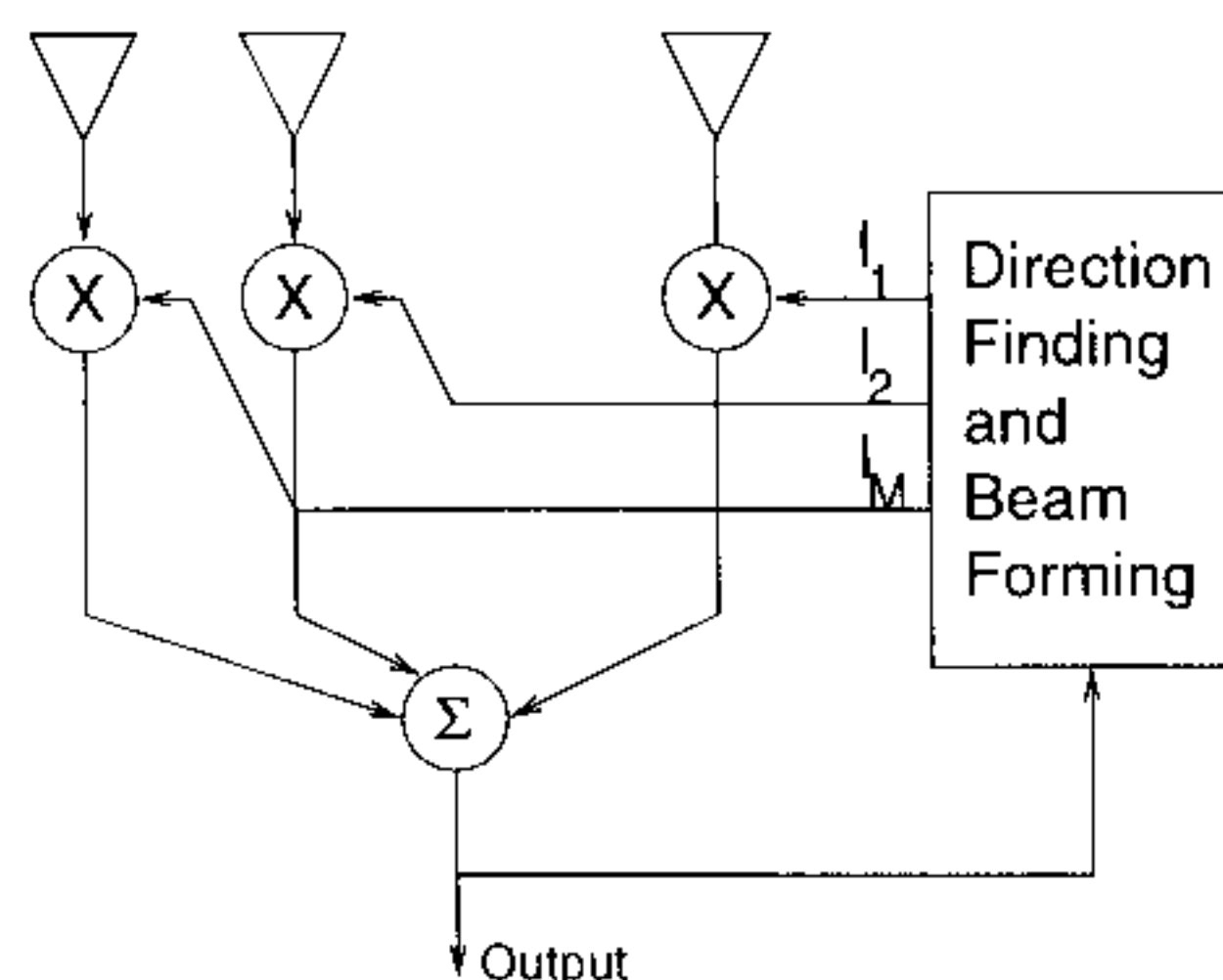


Fig. 5. An M-element adaptive array with a beamforming and direction finding processor.

Figure 5 shows an M-element adaptive antenna array with a processor that performs the calculation of the direction of the desired signal, as well as the set of antenna weights required to focus the antenna radiation pattern on the desired signal. Typically, the radiating elements of an adaptive antenna array is separated by $\lambda/2$, where λ denotes the wavelength of the carrier signal. The operation of a SDMA system implemented in a TDMA environment using antenna arrays is depicted in Figure

2. Transmission from the named target mobiles occur at the same time instant, and the beam of the BS antenna is formed to maximize the received signal power from these target mobiles, whilst the received power from other interfering mobiles (inside this particular cell, as well as from adjacent cells) are minimised through the introduction of nulls in the antenna radiation pattern. Note that in the case systems using code division as multiple access method, the picture changes. In general, it can be assumed that the number of subscribers active in a cell will be larger than the number of elements in an array, that is greater than the freedom levels of the adaptive system. All of these subscribers are transmitting in the same frequency band at the same time instant, meaning null steering cannot be performed. At best *beam steering* can be used to point the main beam in the direction of a desired user or group of users [2]. Many algorithms exist for the adaptation of the weights associated with each radiating element and for the combining of signals received on radiating elements. These include the Bartlett, Capon [18], Least Mean Squares (LMS) [21]. Constant Modulus Algorithm (CMA) [22] and Maximal Ratio Combining (MRC) [23] algorithms. These will not be covered in detail in this paper, however, an excellent overview can be found in [18] with notable contributions presented for example in [2], [20], [24], [25], [21], [22], [26], [23].

III. ANTENNA ARRAYS

Many excellent text describing the operation of antenna arrays are available [18], [10], [20], [4], and this work will not be duplicated. In this section, a short overview of the different types of antenna arrays and the basic operating principles of an adaptive antenna array - especially those of importance too cellular and communications engineer are reviewed.

Many different type of antenna arrays and systems are found in practice and in the literature. An uncomplete list would include arrays such as uniform arrays, broadside arrays, end-fire arrays, phased (scanning) arrays, planar arrays and distributed antennas. To complicate matters even further, the word adaptive may be added to each of these. Whereas Definition 10 presented a general definition for an adaptive antenna array, it is worth explaining the difference between the above mentioned antenna arrays and systems, as it applies in this paper.

Uniform arrays are arrays of identical elements with identical excitation amplitudes, each with progressive phase.

Broadside arrays have maximum radiation directed normal to the axis of the array ($\phi = 90^\circ$ in Figure 6)

End-fire arrays have maximum radiation along the axis of the array ($\phi = 0^\circ$ in Figure 6)

Phased arrays are either broadside or end-fire arrays in which the phase difference between excitation currents can be controlled to point the main beam in any desired direction.

Planar arrays are formed by placing radiating elements along a rectangular grid. These arrays are more versatile and can provide more symmetrical patterns with lower side lobes [10]. Furthermore, essentially any other array configuration can be derived from a planar array, as is shown next.

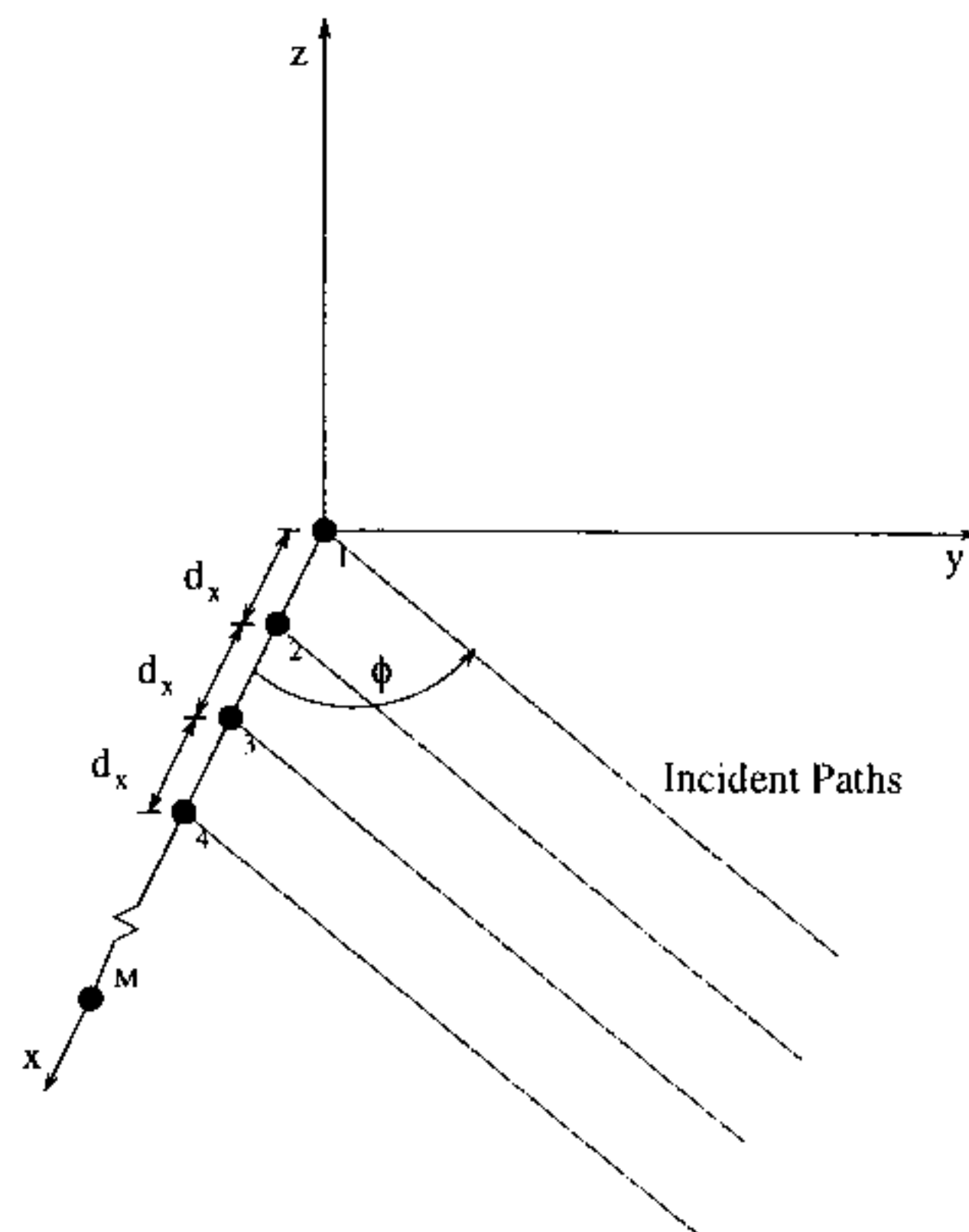


Fig. 6. Uniform Linear Array (ULA).

The total field of an array is determined by the vector addition of the fields radiated by the individual elements of the array. To create arbitrary directive patterns, it is necessary that the fields from the individual elements of the array interfere constructively in the desired directions, and destructively in the remaining directions. In an array of identical radiating elements, four main variables can be used to control the shape of the overall pattern of the antenna [10]. These are:

1. The array geometry (linear, circular etc. (see Figure 8)).
2. The relative displacement between elements.
3. The excitation amplitude of individual elements.
4. The excitation phase of individual elements.

To understand how these variables influence the design of an antenna array system, consider the $M \times N$ -element planar array shown in Figure 7. As-

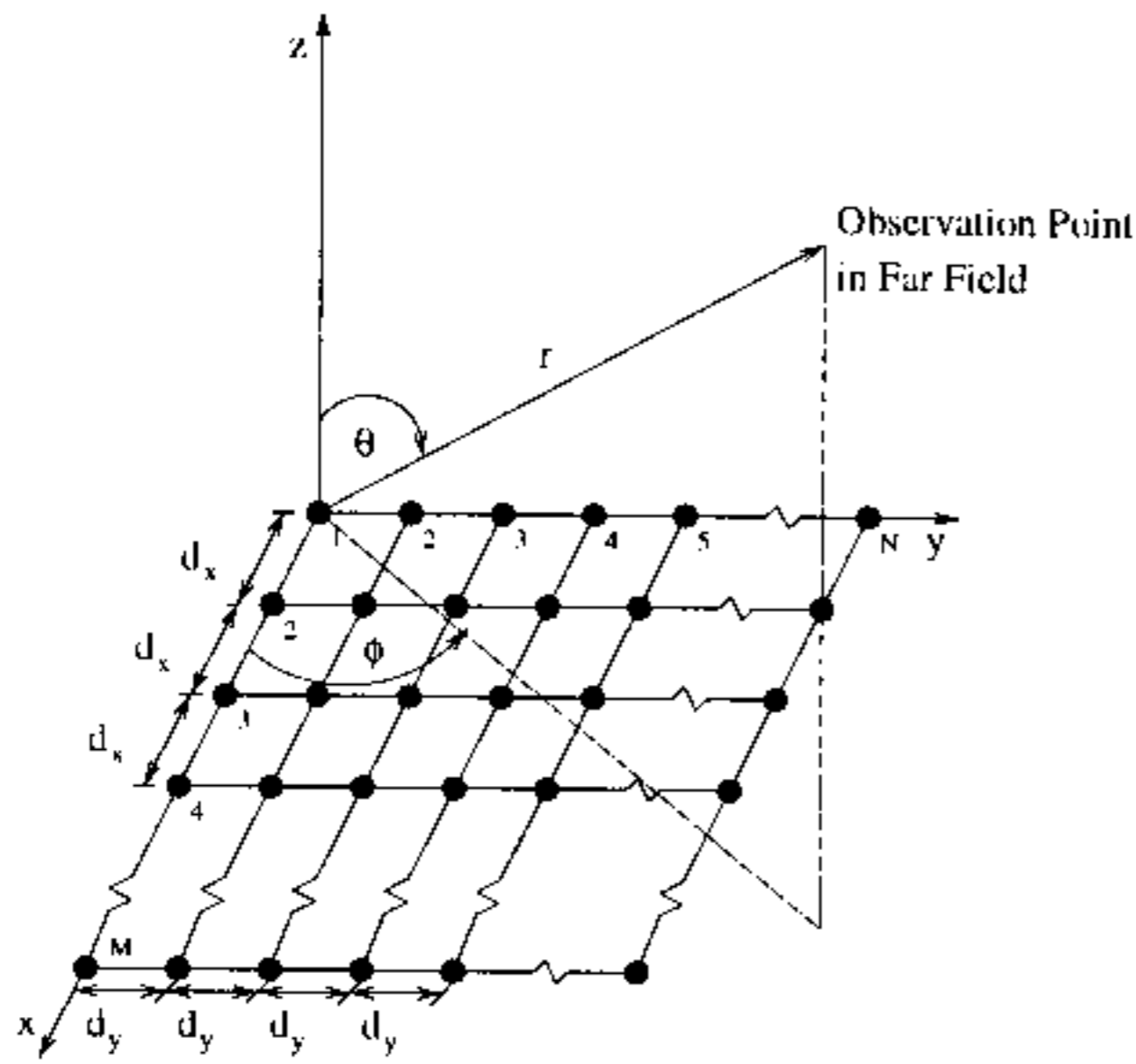


Fig. 7. MxN element Planar Array.

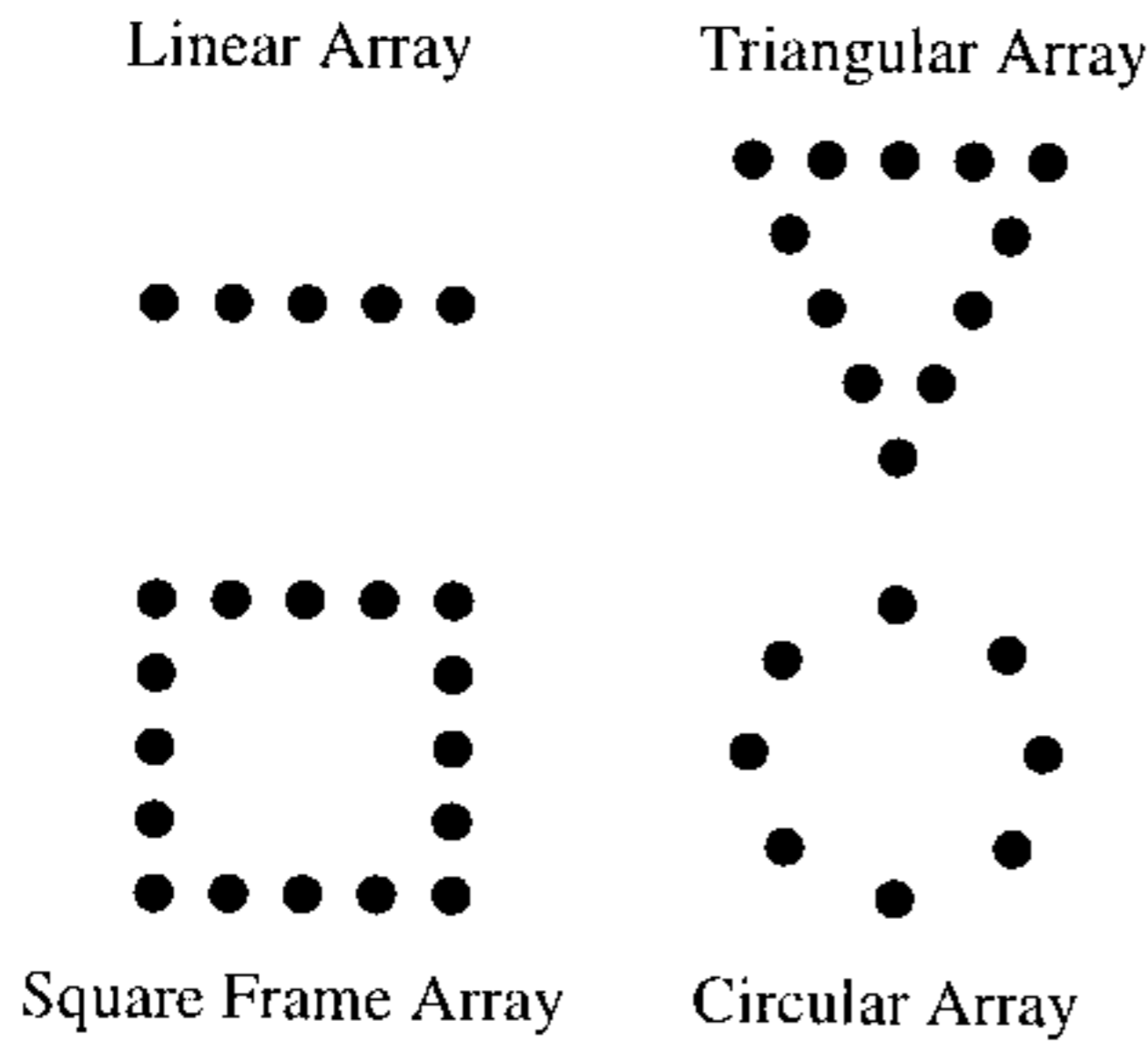


Fig. 8. Some common array geometries.

suming that all radiating elements are the same (eg. elementary dipoles) the total field of the antenna array is defined as the field of a single element, at a selected reference point (usually the origin), multiplied by the array factor of that array [10]. That is,

$$\bar{E}_{total} = \bar{E}_{\text{single element at reference point}} \times AF \quad (2)$$

where \bar{E} denotes the matrix describing the electrical field of the array and AF denotes the array factor of the array. The array factor describes the spatial properties of the antenna beam and, assuming that the amplitude excitation coefficients of the elements of the array in the y -direction are proportional to those in the x -direction, is defined as

$$AF = \sum_{n=1}^N \sum_{m=1}^M I_{nm} e^{j(m-1)\mathcal{X}} e^{j(n-1)\mathcal{Y}} \quad (3)$$

where $\mathcal{X} = kd_x \sin \theta \cos \phi + \beta_x$, $\mathcal{Y} =$

$kd_y \sin \theta \cos \phi + \beta_y$, I_{nm} denotes the complex excitation coefficient of the radiating element at coordinates (m, n) , $k = 2\pi/\lambda$ and β_x and β_y denote the progressive phase shifts between the excitation currents to elements along the x and y axis respectively. Most often, the antenna factor is presented in vector form to yield the *steering vector* (other names include action vector, array propagation vector and signal replica vector [18]). The general steering vector representing the planar array of Figure 7 is then shown in (4).

$$\bar{a}(\theta, \phi) = \begin{pmatrix} I_{11} & \dots & I_{1M} e^{j(M-1)\mathcal{X}} \\ \vdots & \ddots & \vdots \\ \vdots & I_{nm} e^{j(m-1)\mathcal{X}} & \vdots \\ I_{N1} e^{j(N-1)\mathcal{Y}} & \dots & I_{NM} e^{j(M-1)\mathcal{X}} \\ & & e^{j(N-1)\mathcal{Y}} \end{pmatrix} \quad (4)$$

Clearly, by setting the values of I_{nm} , equation 4 can be used to represent most antenna arrays. For example, consider the linear array depicted in Figure 6. When the excitation coefficients of all the radiating elements are equal, the array is said to be uniform [10], hence Figure 6 depicts an Uniform Linear Array (ULA). In this case, $I_{nm} = 0$ for all $n > 1$. Thus, considering only radiation in the xy -plane ($\theta = 90^\circ$) and assuming that excitation currents are all in phase ($\beta_x = 0$), equation 4 reduces to the well known [10], [18]

$$\bar{a}(\phi) = \left(I_1 \quad I_2 e^{jk d_x \cos \phi} \quad \dots \quad I_M e^{j(M-1)(k d_x \cos \phi)} \right)^T \quad (5)$$

Several array geometries have been considered for use in cellular communication systems. Amongst these are [4], [18] linear arrays, triangular arrays, square frame arrays, circular arrays etc. Figure 8 depicts some of these standard shapes.

IV. SYSTEM ASPECTS INFLUENCING SDMA PERFORMANCE

It should be clear from the discussion above that the gain offered by a SDMA system will rely on many parameters, some of which are beyond the control of the design engineer. Specifically three main areas of influence can be identified namely, (i) the propagation path of the signal, (ii) angular distribution of subscribers and (iii) the Quality of service required by each subscriber. In this section, it is shown how each of these aspects influences the gains of a SDMA network.

A. Propagation Path

The modeling of the propagation path needs to take into account a number of effects. These in-

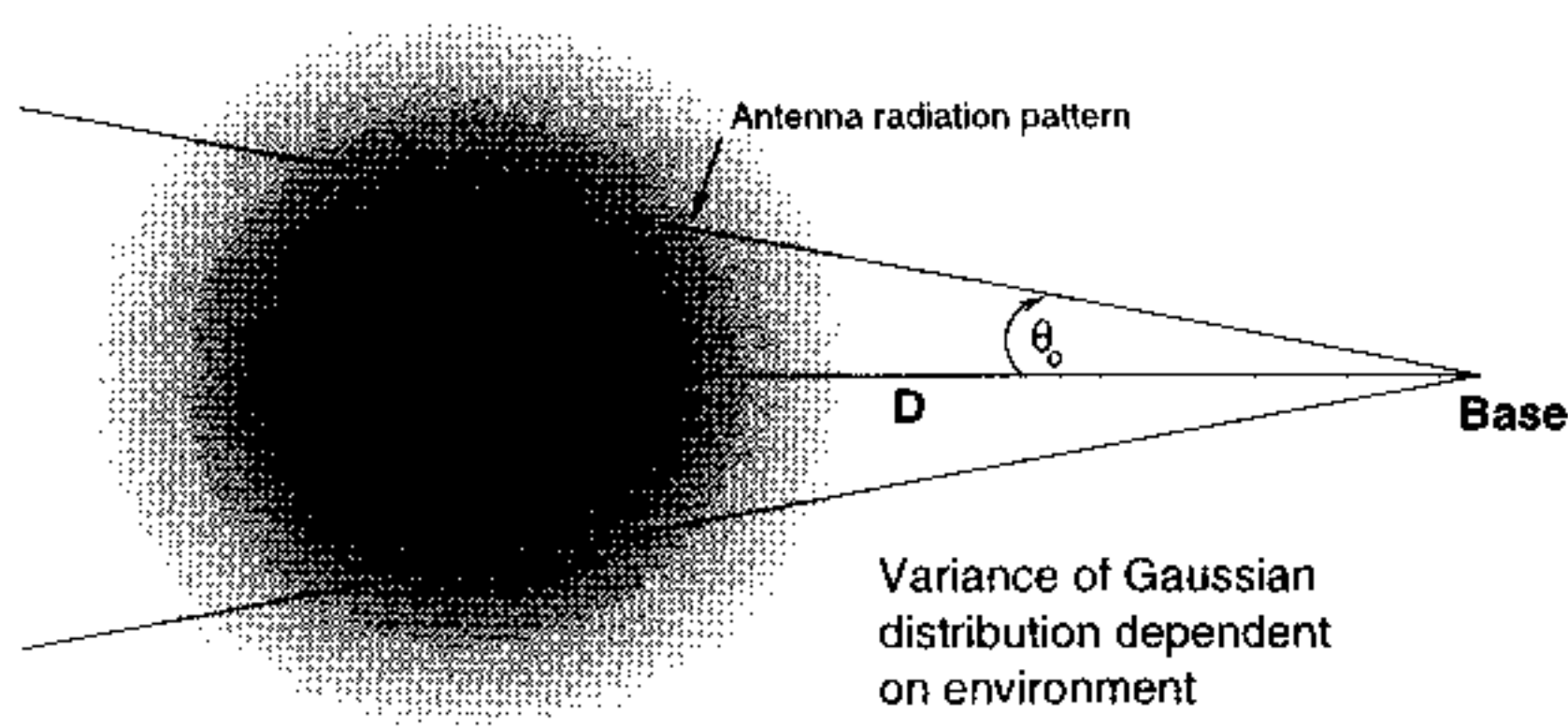


Fig. 9. Gaussian distribution of local scattering elements generate correlated multipath echos.

clude

- Path (propagation) loss
- Shadowing
- Number of multipath components and the distribution of their envelopes
- Local scatterers.

The latter effect is of particular importance to the operation of smart antenna systems. Multipath components generated by a single area of local scatterers may show considerable correlation. The amount of correlation depends heavily on assumptions made concerning the spatial distribution of local scattering elements. Two main approaches have been used in literature, namely the ring-of-scatterers approach [20] and the Gaussian distribution [27]. Consider the situation depicted in Figure 9. In [27] it is shown that if a bell-shaped spatial Gaussian model for the distribution of scatterers around the subscriber is assumed, then the angular distribution of received signals at the receiving antenna is also Gaussian. Given this, there is a Fourier transform relationship between angular distribution and the transverse spatial correlation at the antenna. If the angular standard deviation is σ_θ radians, the crosscorrelation of the fading between antenna elements separated by x meters is

$$p(x) = e^{-\frac{4\pi x^2 \sigma_\theta^2}{\lambda^2}} \quad (6)$$

where λ denotes the wavelength of the carrier frequency.

The above mentioned propagation characteristics influence mainly the performance of the angle of arrival estimation algorithm used, as well as the performance of the combining algorithm used in the case of SDMA systems relying on both beam steering and diversity techniques. Most angle of arrival estimation algorithms used assume that the signals arriving at each element of the array are highly correlated. From (6) it is clear that this assumption

will depend heavily on the composition of the local scattering area surrounding the mobile.

B. Angular distribution of subscribers

In [28] it is shown that the distribution of the angle-of-arrival of signals in a cellular system is dependent on both the distribution of subscribers in a cell, as well as the distribution of scattering elements around each subscriber. Specifically, the manner in which subscribers are clustered together in angle (as would be the case on a road), significantly influences the gains that may be achieved by a smart antenna or SDMA system. For instance, if the reference user and an interfering user are co-located in angle, no antenna pattern can be formed in either the up- or downlinks to reduce the interference seen by the reference user. Therefore, the gain offered by for instance a SFIR system to users in the relevant cell is negligible. On the other hand, having subscribers cluster in certain areas means that antenna sectors can be narrowed, thereby reducing interference to adjacent cells and increasing the overall network performance, even if the performance of all individual cells are not increased.

C. Quality of service requirements

The introduction of different types of services into the network will create what we term, *Quality Of Service Inhomogeneity (QOSI)*. Consider the scenario depicted in Figure 10. Assuming that subscribers in the shown cell are uniformly distributed, the obvious choice for an antenna radiation pattern would be isotropic. However, if a limited number of subscribers in the cell require services with BER requirements substantially stringer than that for voice communication the picture changes. For instance, in Figure 10 most of the subscribers require voice service with typical BER requirements of 1×10^{-3} whereas another subscriber require a video service with a BER of 1×10^{-6} and yet another require a data service with a BER requirement of 1×10^{-8} . Using standard BER graphs for BPSK signaling as an example [29], this translates to approximately 2dB extra signal power for the case of the voice transmission and 4dB in the case of the data transmission. Now, in stead of using more powerful error correcting codes or higher bandwidths for the video and data stream, it is also feasible to slightly alter the antenna radiation pattern to radiate the required extra signal power to the subscribers needing higher quality services.

V. CONCLUSIONS

In this paper, the basic principles of smart antenna systems, such as HSR, SFIR and SDMA have

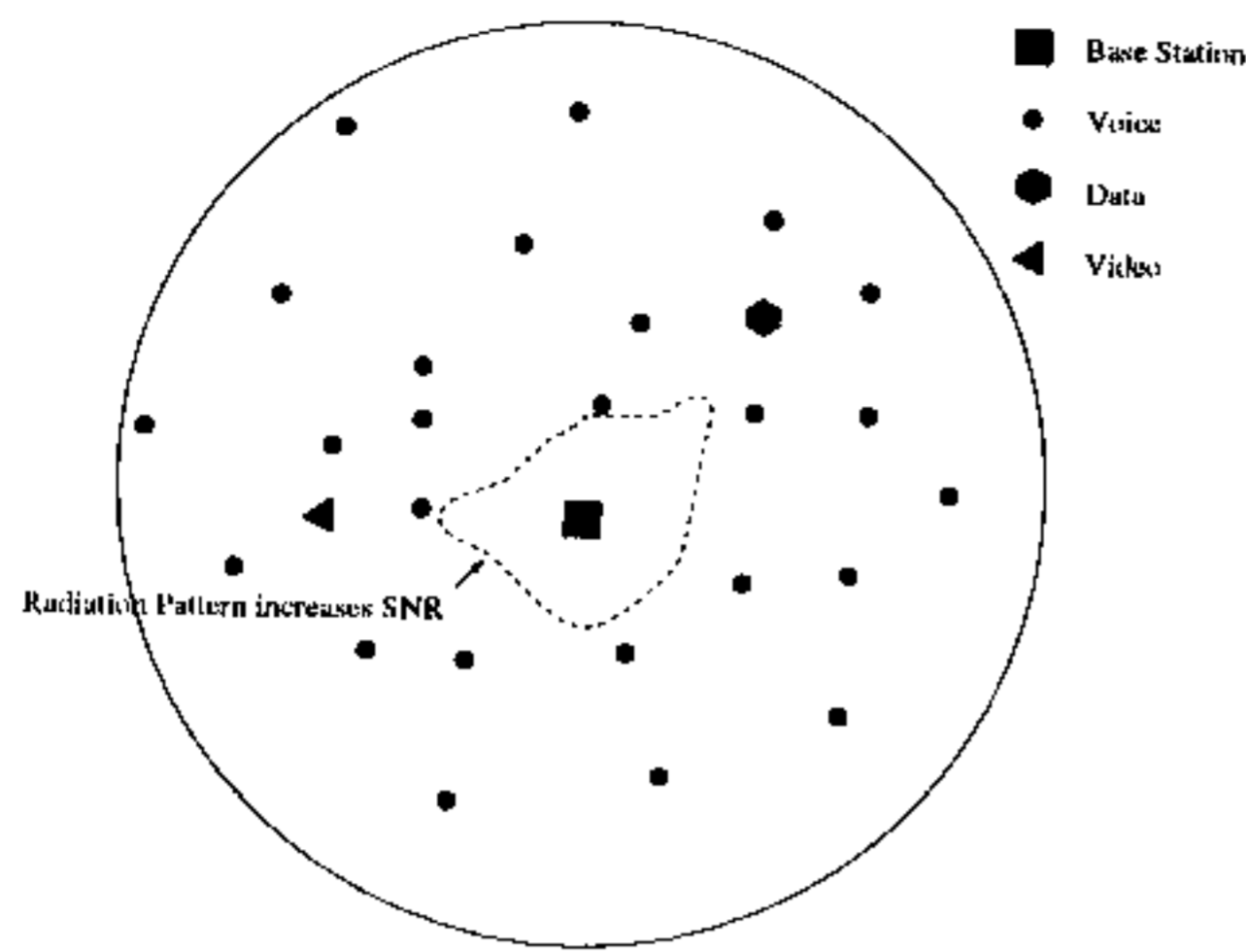


Fig. 10. Quality Of Service Inhomogeneity (QOSI) supported using adaptive antenna arrays.

been reviewed, and their operation has been explained qualitatively. It has been shown that spatial optimization techniques may in many cases lead to significant improvements in system capacity. Three key aspects that influence the system gains offered by SDMA systems have been reviewed and a new application of smart antenna systems for the control of the Quality of Service in cellular networks with heterogeneous services was introduced.

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