

# 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 are 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 [1]. 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 [1].

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 [2] would have sounded far fetched. Today this is reality. The European Telecommunication Standards Institute (ETSI) have recently decided to adopt Wideband CDMA (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 in-

roduction 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 [3], [4], [5] 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 [6]

*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. Section III 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, some conclusions will be presented in section IV.

## 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 [7] and CT-2 [8]), 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 [8]), 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 [8]) 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.

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In [9], [10], [11], 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* [9], [11] (with the data rate measured as some predefined Bit Error Rate (BER)), *Erlang/MHz/km<sup>2</sup>*, equivalent telephone Erlangs per square kilometer [12] and even *Mbit/s-per-floor* for indoor environments [12]. 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 ( $\eta$ )**

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,  $\eta$  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 *km<sup>2</sup>*, occupied by the re-use cluster. Clearly, the concept of the re-use cluster is fundamental in the determination of  $\eta$ . Definitions for a re-use cluster can be found in [11], [13]. 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.

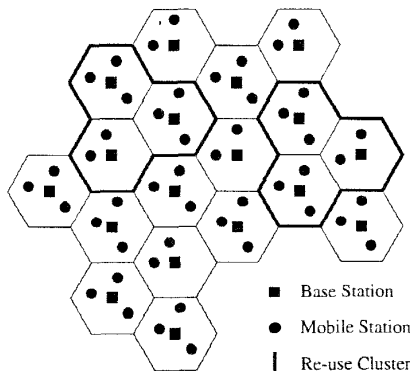


Fig. 1. Cellular re-use concept.

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) [6].

**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 [14] 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.

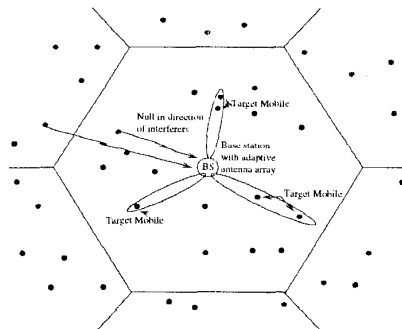


Fig. 2. SDMA system implemented using adaptive antenna arrays.

In a manner similar to HSR, Spatial Filtering for Interference Reduction (SFIR) [6] 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 mo-

ble), 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 [3], [5], [4]. 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.*

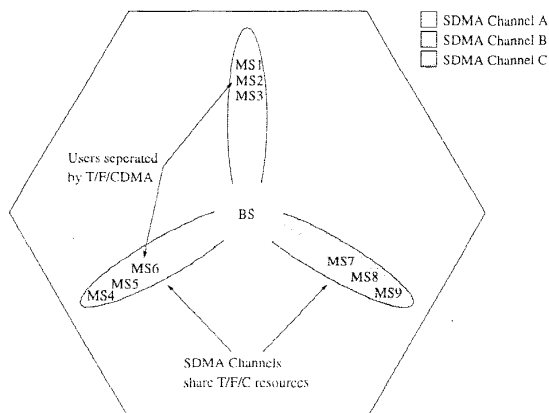


Fig. 3. Space Division Multiple Access (SDMA): Allowing users in the same cell to share time/frequency and code resources.

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. In [6] it is shown analytically and by measurements that gains in the order of 5-9 dB can be obtained using antenna arrays with 8 elements.

### III. 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 two main areas of influence can be identified namely, (i) angular distribution of subscribers and (ii) the Quality of service required required by each subscriber. In this section, it is shown how each of these aspects influence the gains of a SDMA network.

#### A. Angular distribution of subscribers

In [15] 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.

#### B. 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 4. 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 4 most of the subscribers require voice service with typical BER requirements of  $1 \times 10^{-3}$  whereas another subscriber require a video service with a BER of  $1 \times 10^{-6}$  and yet another require a data service with a BER requirement of  $1 \times 10^{-8}$ . Using standard BER graphs for BPSK signalling as an example [16], 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, instead 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.

## IV. CONCLUSIONS

In this paper, the basic principles of smart antenna systems, such as HSR, SFIR and SDMA have been reviewed, and their operation have been explained qualitatively. It has been shown that spatial optimization techniques may in many cases lead to significant improvements in system capacity. Two 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.

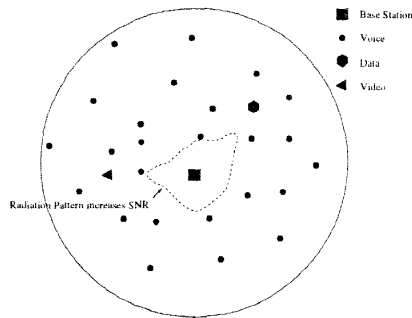


Fig. 4. Quality Of Service Inhomogeneity (QOSI) supported using adaptive antenna arrays.

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