SDMA IN MOBILE RADIO SYSTEMS: CAPACITY ENHANCEMENT IN GSM & IS-95.

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ABSTRACT

The Space Division Multiple Access (SDMA) technique allows to increase the capacity of a mobile cellular system, exploiting the users spatial separation.This technique can be integrated with conventional access techniques, such as FDMA, TDMA and CDMA; therefore it can be used in all the mobile systems currently operated or to be introduced in the future.
In this paper the SDMA technique is deeply analysed. It also evaluates the capacity increase obtainable with SDMA applied to GSM and to a CDMA (Code Division Multiple Access) system, based on Qualcomm IS-95 standard.

1. INTRODUCTION

Mobile radio communication systems are currently characterised by an ever-growing number of users, which however is coupled with limited available resources, in particular in terms of usable frequency spectrum. Research is therefore oriented towards developing new access techniques, for a more efficient employment of available frequency bands.
The Space Division Multiple Access Technique allows to enhance the capacity of a cellular system by exploiting spatial separation between users [1]. In an SDMA system, the base station does not transmit the signal throughout the area of the cell, as is the case of conventional access techniques, but rather concentrates power in the direction of the mobile unit the signal is meant to reach, and reduces power in the directions where other units are present. The same principle is applied for reception.
The SDMA technique has several characteristics which make its introduction in a mobile radio system advantageous. In particular, all modifications required are limited to base stations, and do not involve mobile units. Moreover, the SDMA technique can be integrated with different multiple access techniques (FDMA, TDMA, CDMA), and therefore it can be used in all mobile radio systems currently operating or about to be introduced [2].
This paper analyses the SDMA technique and the different ways in which it can be introduced in a mobile radio system. It also evaluates the capacity increase obtainable with the SDMA technique in FDMA/TDMA mobile radio systems, such as the European system GSM, and in a CDMA system, based on Qualcomm IS-95 standard.

2. SDMA, Space Division Multiple Access

In traditional cellular systems the base station, having no information on the position of mobile units, is forced to radiate the signal in all direction, in order to cover the entire area of the cell. This entails both a waste of power and the transmission, in the directions where there are no mobile terminals to reach, of a signal which will be seen as interfering for co-channel cells, i.e. those cells using the same group of radio channels. Analogously, in reception, the antenna picks up signals coming from all directions, including noise and interference.
These considerations have lead to the development of the SDMA technique, which is based on deriving and exploiting information on the spatial position of mobile terminals. In particular, the radiation pattern of the base station, both in transmission and reception, is adapted to each different user so as to obtain, as shown in Figure 1, the highest gain in the direction of the mobile user. Simultaneously, radiation nulls shall be positioned in the directions of interfering mobile units. This behaviour is just defined “null steering” [3].

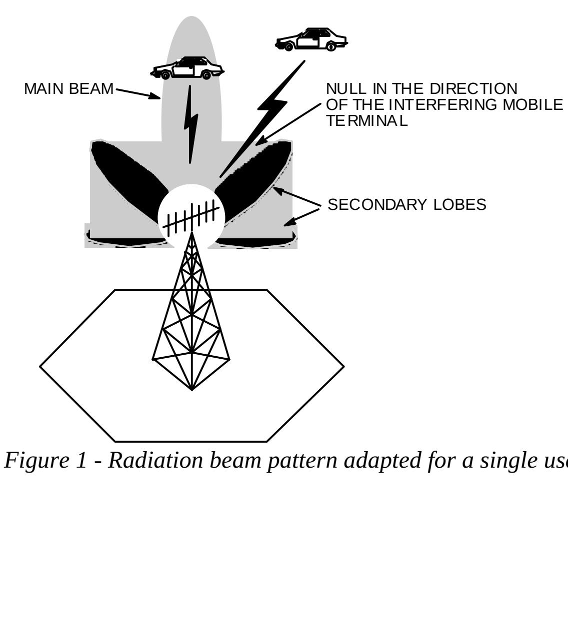

Figure 1 - Radiation beam pattern adapted for a single user

This requires the capability to carry out spatial filtering, which can be obtained by using, at the base station, an adaptive antenna array [4], [5], [6], whose operation is illustrated in Figure 2. The reciprocal scheme is used in transmission.

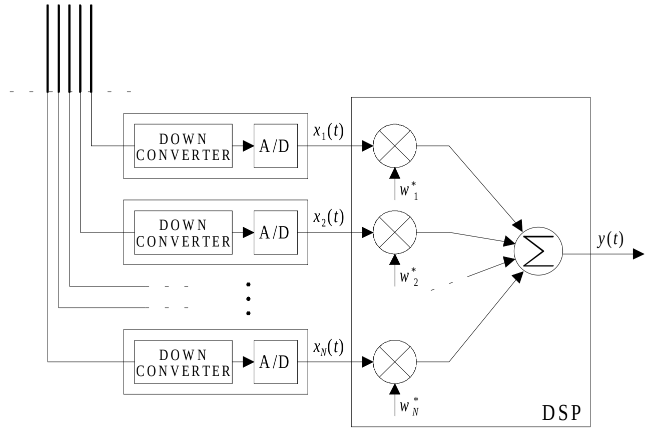

Figure 2 - Structure of an adaptive antenna array in reception

This system thus comprises an array of antennas and a Digital Signal Processor (DSP) tasked with real time processing of signals received or to be sent to the different antennas.

With reference to Figure 2, it can be observed that the RF signal received by each of the N antennas comprising the array is at first brought down to base band and then converted into digital form. The N complex signals obtained are then sent as inputs to the DSP, which multiplies the signal of each antenna by a suitable factor wi*, and finally adds the various terms. The output signal is therefore given by:

$$y(t) = \sum_{i=1}^{N} w_i^* x_i(t). \tag{1}$$

An appropriate choice of the weights vector w = [w1, w2, ...wN] allows to give the radiation pattern the desired characteristics. In particular, vector w is determined using an adaptive strategy. Coefficients are therefore updated periodically, based on the observation of data received. To assure correct operation of the system, it is necessary that the adaption rate could compensate the environmental variations, due to the mobility of the sources and accentuated by the presence of multiple paths.

The use of an adaptive antenna array at the base station thus allows to introduce the SDMA technique, whose main advantage is the capability to increase system capacity, i.e. the number of users it can handle. This increase can be obtained in two different ways, and therefore the following applications are possible [1], [2]:

Reduction in co-channel interference

The reduction in the level of co-channel interference between the different cells using the same group of radio channels is obtained, as above seen, by minimising the gain in the direction of interfering mobile units. This technique, indicated with the acronym SFIR (Spatial Filtering for Interference Reduction) allows to reduce frequency re-use distance and cluster size. In this way, each cell can be assigned a higher number of channels.

Spatial orthogonality

In conventional access techniques, orthogonality between signals associated with different users is obtained by transmitting them in different frequency bands (FDMA, Frequency Division Multiple Access), in different time slots (TDMA, Time Division Multiple Access) or using different code sequences (CDMA, Code Division Multiple Access). Using an antenna array, it is possible to create an additional degree of orthogonality [7] between signals transmitted to and from different directions. It is thus possible to assign the same physical channel to several mobile units, as depicted in Figure 3, when the angles at which they are seen by the base station are sufficiently separated. The result is an increase in the number of available channels, since the same physical channel, for example the same carrier in a FDMA system or the same time slot in a TDMA system, can be subdivided into multiple spatial channels, each of which is assigned to a different user.

It must be noted that the term “SDMA” refers, strictly speaking, only to the latter application, in which a space division multiple access is actually accomplished. In spite of this fact, the SFIR technique is also considered within the SDMA technique, since it is based on the same principles.

In addition to the opportunity to increase system capacity, the SDMA technique has additional characteristics making its introduction in a mobile radio system advantageous [1], [2]. In particular, it is possible to exploit the higher receive gain offered by an antenna array with respect to an omnidirectional case, to allow mobile units to transmit at reduced power, and therefore lower consumption. At equal power, gain can be exploited to extend cell size. This is useful when it is necessary to cover vast surface areas (typically rural areas), characterised by a low mobile radio traffic density, with a limited number of base stations.

Moreover, there is a reduction of the multipath fading effects, by carefully choosing weight vector w, it is possible to select only one or more multiple paths, which are added coherently, thus avoiding destructive interference and limiting received power reduction [6].

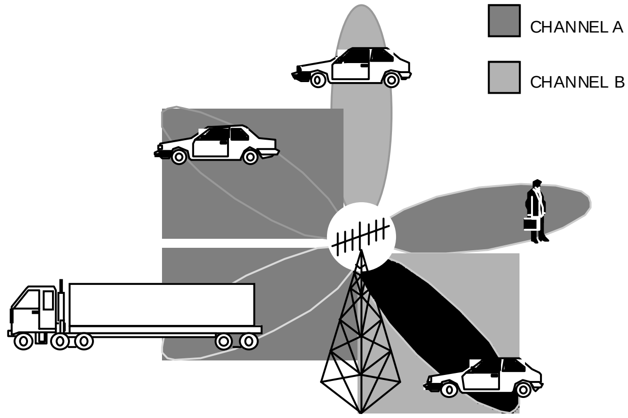

Figure 3 - Space Division Multiple Access: multiple users belonging to the same cell use the same channel

The SDMA technique can also be integrated with all the different multiple access techniques in use (FDMA, TDMA, CDMA), and therefore can be applied to any mobile radio system. However, we shall see that the ways in which the SDMA technique can be introduced and the advantages it provides differ depending on the system under consideration.
As aforesaid described, modifications required to realise the SDMA technique are limited to the base station, and thus do not involve mobile units. This allows to introduce this technique in existing mobile radio systems, with no need to modify their characteristics.

3. SDMA in FDMA/TDMA mobile radiosystems

In a Frequency and Time Division Multiple Access mobile radio system, capacity is limited by two different factors. On one hand, a limited number of radio channels (carriers and time slots) is available, and they must be subdivided among cells making up a cluster. On the other hand, co-channel interference limits channel re-use.
The SDMA technique allows to expand both these limits and therefore to enhance system capacity. As already described, this can occur in two different ways: with the SFIR technique, interference level is reduced and channel re-use distance is decreased, whereas the actual SDMA technique assigns the same channel to multiple, spatially separated, users.
It can be seen that the SFIR technique requires to plan anew the frequencies associated to different cells, which is not required by the SDMA technique: thus, the advantage of the latter is that it can be introduced in cells serving areas that are particularly critical in terms of mobile radio traffic, with no need to involve bordering cells and to modify the structure of the cluster.
On the other hand, the SDMA technique requires an array composed of more antennas than the SFIR technique does; in fact spatial orthogonality is exploited by eliminating, through the use of spatial filtering, intra-cell co-channel interference, which is due to mobile units belonging to the same cells and using the same channel as the mobile unit in question. The power level at which the base station receives signals transmitted by these mobile units is comparable with that of the useful signal. It is therefore necessary for the radiation pattern associated with the desired user to have, in the directions of these interfering units, very deep nulls, compared with those sufficient, in the SFIR technique, to suppress co-channel interference from other cells. This is shown in Figure 4, where radiation patterns for two mobile units sharing the same channel are depicted. To obtain such a selective response, it is necessary for the antenna array to be highly directive, and therefore for the number of antennas to be high. This increase in the number of antennas is not only difficult to accomplish, but also presents control algorithms with high computational complexity, which results in lower adaptation speed and therefore in problems handling fast-moving mobile units.

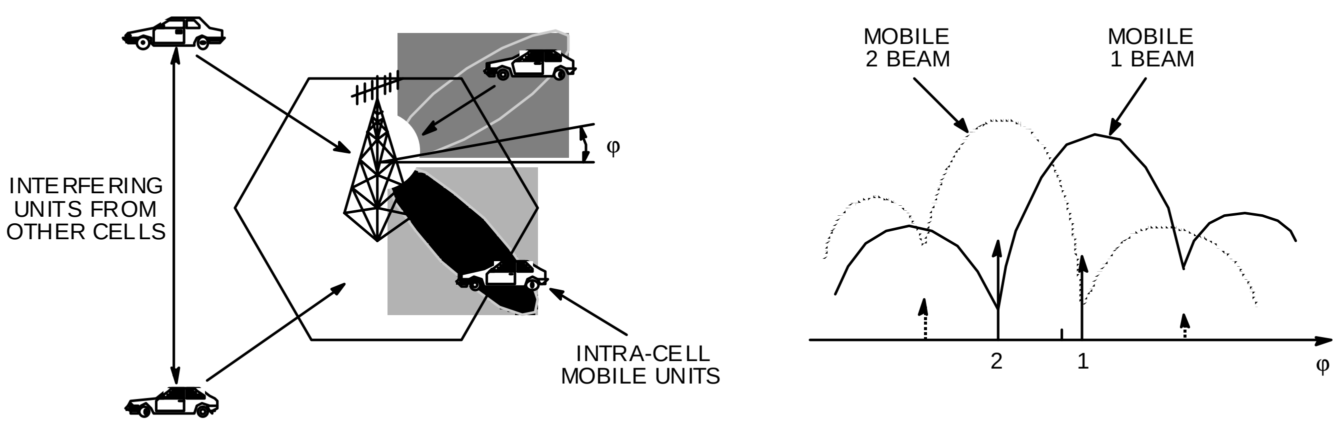

Figure 4 -Radiation patterns associated with two users sharing the same channel.
Deeper nulls must be aimed in the direction of the intra-cell interfering unit

As already stated, Space Division Multiple Access can only take place if there is sufficient angular separation between users. The minimal angle for which signals can still be correctly separated also depends on the number of antennas. When two mobile units sharing the same physical channel move closer to each other, it is necessary to force one of them, through suitable signalling, to abandon the channel and to use another one where there are no mobiles in the direction under consideration. Thus, an intra-cell hand-over procedure is required.

The number of users who can share the same channel, i.e. the number of spatial channels which can be allocated in the same physical channel, is called Spatial Multiplexing Gain (SMG) [1]. From the considerations above, it can be readily seen to be closely linked to the number of antennas in the array.

Performance attainable with the SDMA technique has been evaluated with the help of a purpose-made simulation model, for which some characteristics of the GSM system have been taken as a reference: for instance, power control and the Discontinuous Transmission (DTX) capability, i.e. the ability to reduce transmitted power in the absence of speech activity. A scenario in which base station sites are located with a regular hexagonal structure (Figure 5) was considered.

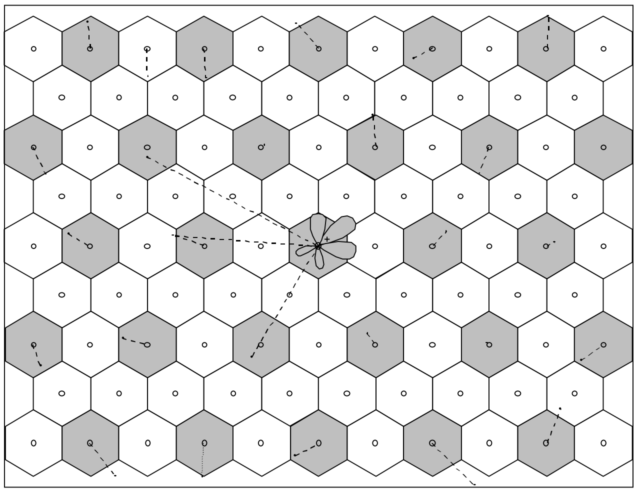

Figure 5 - Simulated scenario for analysing the SDMA technique in a FDMA/TDMA system

A uniform distribution of mobile units is generated in this area, and each mobile unit is locked to the base station from which it receives the highest power level. It was assumed that link attenuation is directly proportional to distance elevated to an exponent $\gamma = 4$. Shadowing effects were also taken into account. The connection between transmitted power P_T and received power P_R is therefore given by the following relationship:

$$P_R = d^{-\gamma} 10^{\eta/10} P_T, \tag{2}$$

where *d* is the mobile unit-base distance and η is a Gaussian random variable with zero mean and standard deviation $\sigma = 8$ dB. For each cell, up to SMG users are allocated in each channel, spatially separated by a minimum angle equal to $2\pi/N$, where N is the number of antennas comprising the array. Note that SMG = 1 leads back to the SFIR case. For mobile units assigned to the base station located in the centre of the area, taken therefore as a reference, the radiation pattern of the antenna array is determined using an MSE (Mean Square Error) criterion, calculating the weight vector w which allows to minimise the following functional [5]:

$$\mathrm{MSE} = \mathrm{E}\left[\left|y_d(t) - y(t)\right|^2\right], \tag{3}$$

that is the mean square error between output signal y(t), given by equation (1), and the desired signal $y_d(t)$. The use of a circular antenna array at the base station was considered: in such an array the different elements are arranged along a circumference at equal distances of $\lambda/4$. This particular structure allows to aim the beam in a 360 degree arc, thus with omnidirectional coverage [9].

Finally, the ratio between useful signal power and total interfering power (C/I, Carrier-to-Interference ratio) is evaluated for the uplink, as the position of the mobile units varies.

For the SFIR technique, it is interesting to evaluate C/I as cluster size varies. Figure 6 shows cumulative C/I distribution for a SFIR system with cluster size C equal to 4, 3 and 1, as the number of antennas, N, varies. The dashed curve refers to the case of a traditional system, using a single omnidirectional antenna. It is evident that the use of an adaptive array allows a 15 to 25 dB improvement in C/I.

For the full SDMA technique, on the other hand, it is necessary to evaluate C/I trend as the spatial multiplexing gain varies, to determine the maximum number of users to share the same channel. Figure 7 again shows the cumulative distribution of C/I, this time evaluated for a fixed cluster size of 4, as the number of antennas N and the SMG parameter vary.

To determine capacity increase over a conventional system, we took as a reference the C/I distribution shown in Figure 8, again evaluated with the model we realised, considering a 3x4 clover type of coverage, which is typical in the GSM system.

It can be noted that, with the SFIR technique, it is possible to reduce cluster size down to a value 1, for which each cell can use all available channels. With respect to a situation with 3x4 cluster, there is a capacity increase by a factor of 4. With the full SDMA technique, the maximum value of SMG, closely connected with N, can reach the value of 8. A value of SMG equal to 4, and therefore an increase in capacity again by a factor of 4, can in any case be seen as reasonable, considering the inevitable margins associated with its practical realisation and the difficulties in using high N values. Note however that, in the SDMA case, it was assumed that a number of mobile units SMG was allocated in each channel. But the SDMA technique may be introduced only in some cells of the system, and not in all of them. In this latter case, given the reduction in co-channel interference from other cells, there would be an increase in C/I and therefore the chance to obtain, in cells using the SDMA technique, a higher SMG.

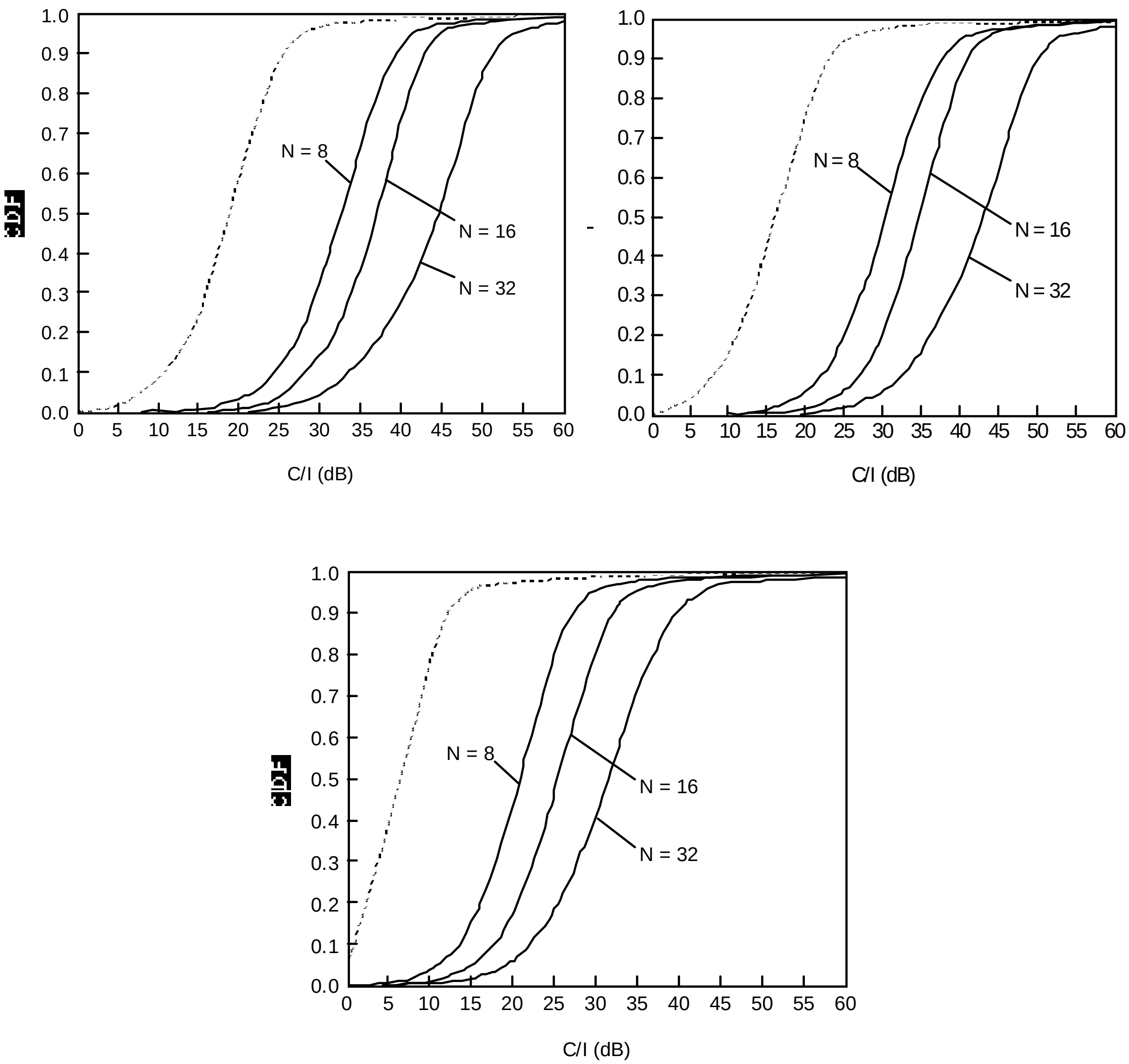

Figure 6 - Cumulative distribution of C/I for a SFIR system with cluster size equal to 4 (left), 3 (right), 1 (bottom)

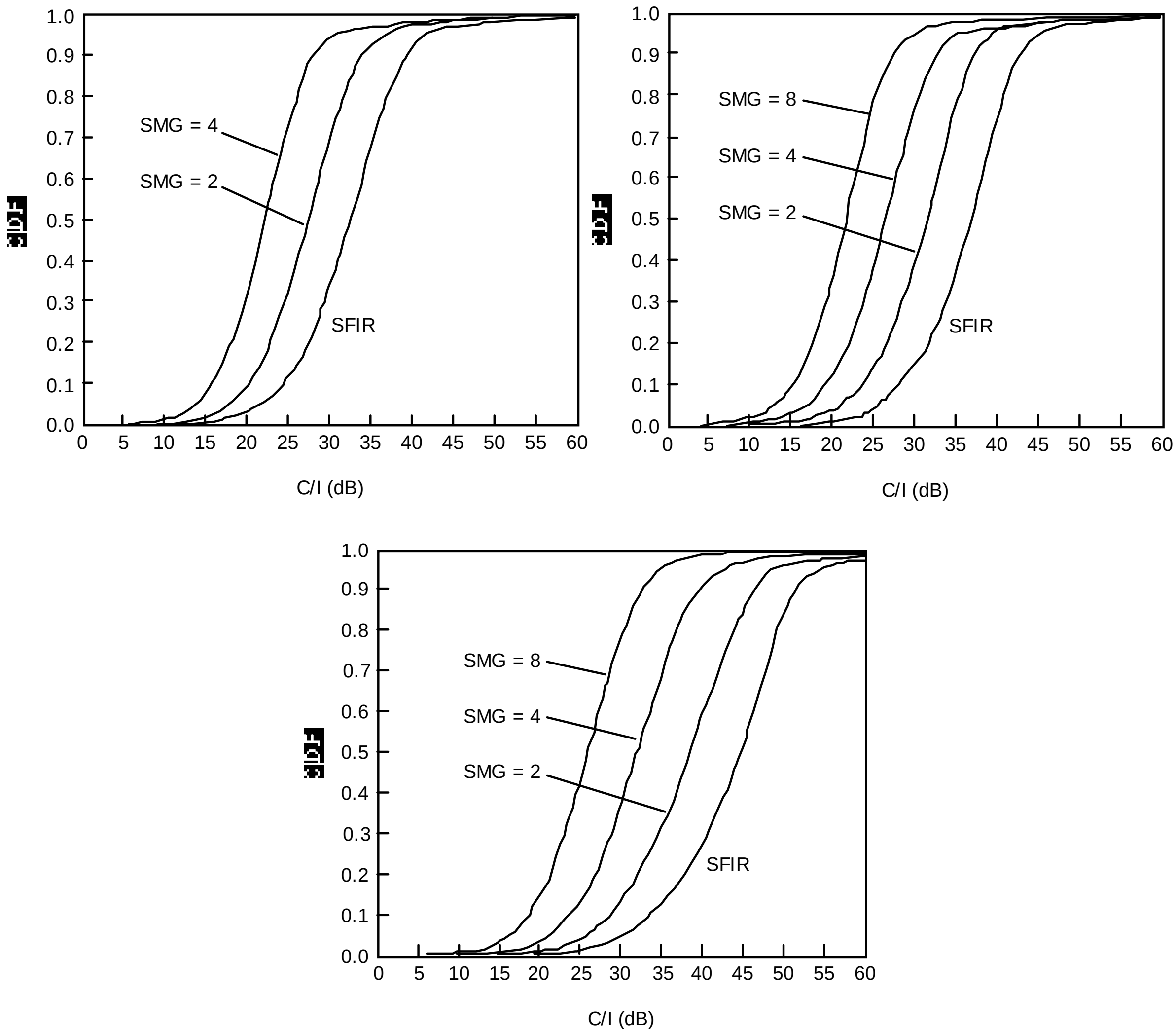

Figure 7 - Cumulative distribution of C/I for an SDMA system, with an antenna array comprising 8 (top), 16 (centre) and 32 (bottom) elements

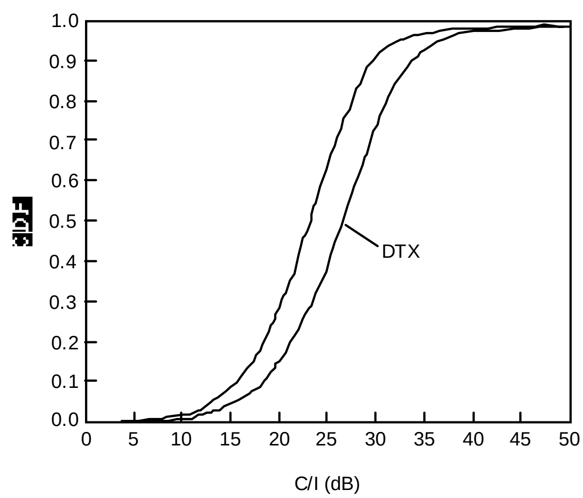

Figure 8 - Cumulative distribution of C/I with a 3x4 clover coverage. The effect of the discontinuous transmission (DTX) capability is highlighted

4. SDMA in a CDMA mobile radio system

In a CDMA cellular system, all users share the entire available frequency spectrum and the same bandwidth is used in all the cells, with the most efficient frequency reuse [10, 11, 12, 15]. The system capacity is now limited, unlike FDMA/TDMA systems, only by the existing interference level. Therefore, each solution aimed at reducing the interference level is directly trasformed in capacity increase[13, 16]. From this considerations it is easy to understand that, in a CDMA system, the SDMA technique cannot be differentiated into SFIR and full SDMA.

Besides, in a FDMA/TDMA only a limited number of interfering mobile units are present for each users, and their signals, in the SDMA technique, must be carefully eliminated by creating nulls in the corresponding directions of arrival. With the CDMA technique, since all mobile units share the same band, the number of potential interfering units is very high, certainly higher than the number of antennas in the array, i.e. the number of degrees of freedom of the adaptive system. Interferent units can also be considered uniformly distributed around the base station. As a consequence, the behaviour of the radiation pattern adaptation system is no longer of the null steering type but instead, as shown in Figure 9, the main beam is simply pointed in the direction of the desired mobile unit [13, 16]. In this way, the reduction in interference level will be only partial. Observe however that, as it is no longer necessary to put nulls in the direction of the interfering units with critical precision, the adaptation system actually requires less complexity.

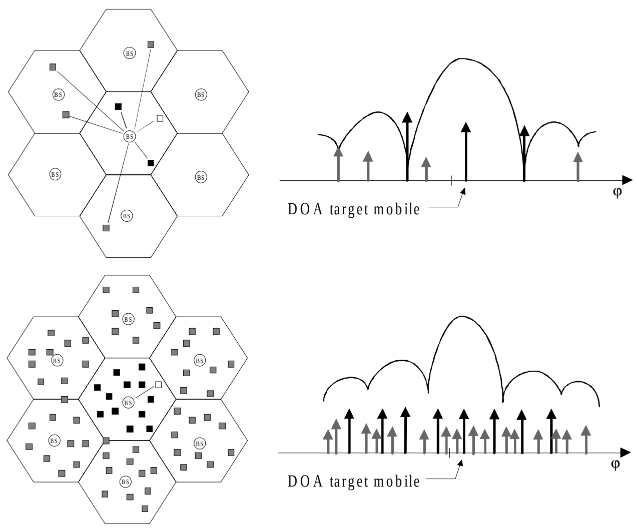

Fig.9 - Radiation beam pattern adaptation in SDMA for a FDMA/TDMA system (upside) and for a CDMA system. In this case there is no "null steering".

The performance obtainable with a combined SDMA/CDMA technique has been evaluated with a simulation model properly realised [16], using a similar model to the one described in the paragraph above. An area (Figure 10) in which a uniform distribution of mobile units is generated has been again considered. The path loss model is again given by equation (2).

Two propagation environments have been analysed, characterised by different γ and σ values, because the capacity of a CDMA system is very sensitive to this aspect. In particular, as in [14], a rural area, here defined by γ=3, σ=6 dB, and an urban area (γ=5, σ=10 dB) have been considered. Besides ideal and continuous power control and Voice Activity Detection (VAD), so that the transmission rate is reduced when there is no speech, have been introduced. The voice activity factor as been assumed equal to 3/8 [14].

The presence of a circular antenna array, where the single elements are disposed on a circumference and equally spaced by a λ/4 distance, has been assumed. This antenna configuration allows to point the beam in a 360 degree arc and, therefore, to cover the cell in all the directions [9].

To evaluate the interference level, it is necessary to determinate the radiation beam pattern of the antenna array. As already said, in CDMA system, there is a high interferer number, uniformly distributed around the base stations. The adaptation system, evaluating the vector **w**, "sees", therefore, besides of the useful signal, an uncorrelated and "spatially white" (in the sense that it is uniformly distributed in all the directions) disturb. In these conditions, the array radiation beam pattern can be appoximated by a phase compensated solution; in fact, it can be demonstrated that this solution is the one that better approximates, on the base of the LMS criterion, the ideal array diagram, unitary in the useful mobile direction and null in all other directions [16]. In Fig. 11 are, for example, compared the radiation pattern of a phase-compensated array and the one obtained by a beamforming algorithm with temporal reference, considering a system with 30 users per cell. The direction of arrival of the useful signal is the zero and a circular array with 16 elements has been considered. It can be noted that the main characteristic of both the diagrams is the pointing of the main beam in the useful mobile direction. For these reasons, in the simulations, a phase-compensated array has been adopted.

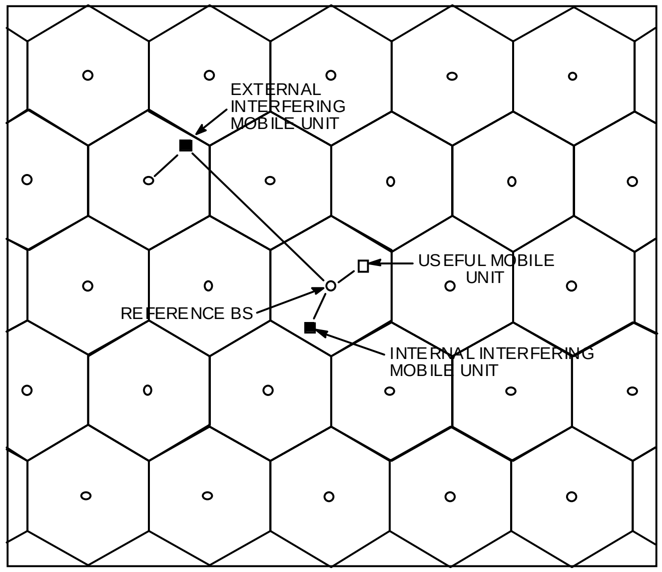

Figure 10 - Simulated scenario for analysing the SDMA technique in a CDMA system

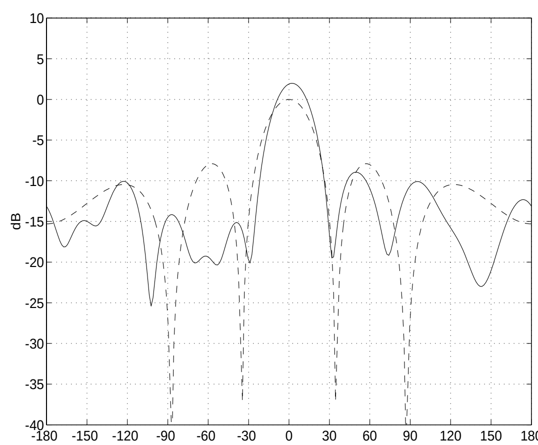

Fig.11 - Comparison among a radiation pattern of phase-compensated array (dotted line) and the one obtained by an adaptive algorithm for a circular array, with N=16

Finally, the Carrier to Interference Ratio, C/I, in the up-link has been evaluated; since no user mobility has been considered, the mobiles random generation and the C/I evaluation processes have been thousands of times repeated, in order to obtain a C/I reliable statistic.
The trend in C/I, evaluated by cumulative distribution at a 10% probability, as a function of the number of users per cell, is shown in Figure 12 and Figure 13, respectively for a traditional system with omnidirectional or 120° sector coverage, and for a system using the SDMA technique, as the number of antennas N changes (N=8, 16, 32) and for the two areas examined. It can be noted that C/I increase is between 5 and 9 dB, and therefore lower than that obtainable in a FDMA/TDMA system. This, as said above, is due to the impossibility to cancel out interfering signals completely by means of “null steering”.
To evaluate the system capacity, a threshold C/I value has to be defined. This value has been obtained by the equation [12]

$$\frac{E_b}{N_0} = G_p \frac{C}{I}, \qquad (4)$$

where G_p is the processing gain. A minimum value for E_b/N_0 equal to 7 dB and a processing gain G_p equal to 128 have been assumed, as in the Qualcomm CDMA system [15]. With these parameters, a C/I threshold value of -14 dB is fixed.
System capacity results [16] are reported in Figure 14. It can be observed that, with the SDMA technique, the increase in capacity over the typical case with 3 sector cells, varies from 2 to 4 times, depending on the antenna array number. In spite of a limited reduction in interference, the result is thus comparable with that obtained for FDMA/TDMA systems.

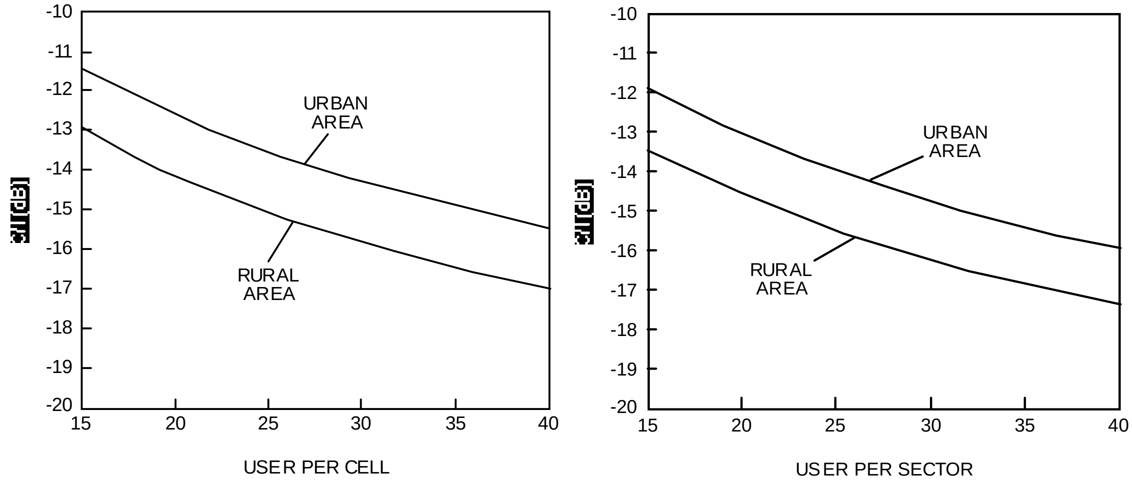

Figure 12 - Trend in C/I ratio, evaluated at a 10% probability, for a CDMA system with omnidirectional coverage (left) and with 120° sector coverage (right) as a function of the number of users per cell or per sector

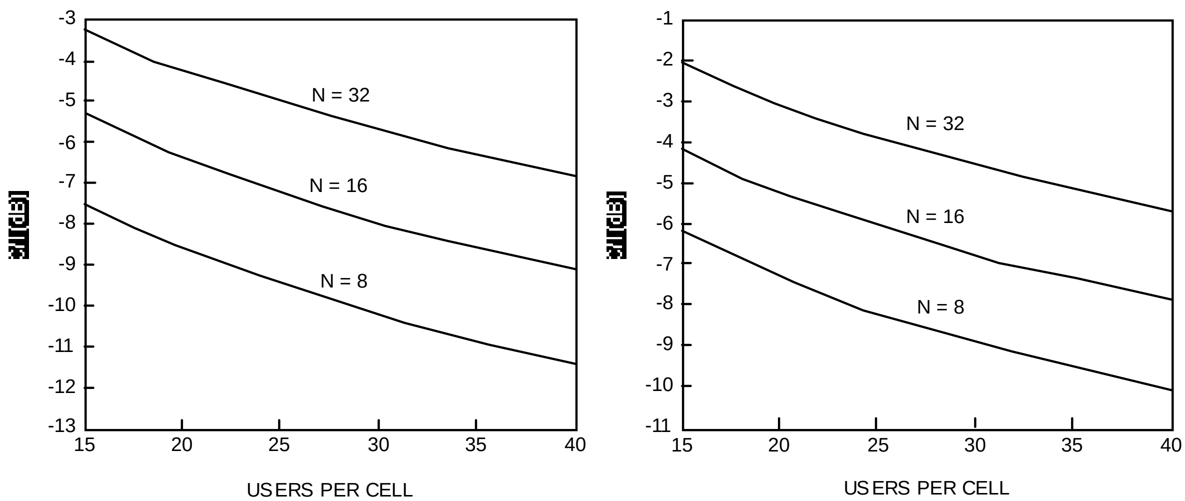

Figure 13 - Trend in C/I ratio, evaluated at a 10% probability, for a CDMA system using the SDMA technique, for a rural area (left) and for an urban area (right)

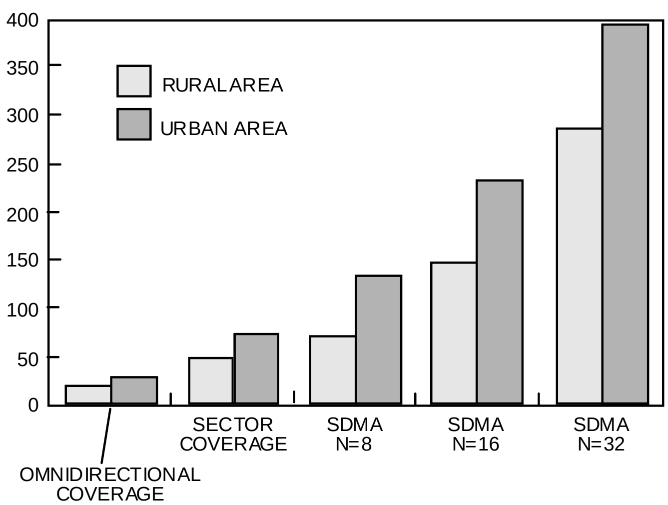

Figure 14 - Capacity of a CDMA system with the SDMA technique

5. Conclusions

In the context of research aimed at finding new solutions to increase the capacity of cellular mobile radio systems, given the continual rise in number of users and the limited available spectrum of frequencies, the Space Division Multiple Access (SDMA) technique was analysed.
The introduction of this technique was found to be advantageous both for currently operational cellular functions, foreseeing that they will eventually reach saturation, and for third-generation mobile radio systems, thanks to the possibility of integrating it with all access techniques currently in use.
We then analysed the different ways to introduce the SDMA technique into a FDMA/TDMA system, such as the GSM system, and into a CDMA system, subsequently evaluating, with the aid of a purpose-designed simulation model, the capacity increase for both systems mentioned above. For the GSM system, the increase in C/I ratio, ranging between 15 and 25 dB, allows to go from a 3x4 clover coverage to a cluster 1, with a four-fold increase in capacity. Alternatively, it is possible to divide each physical channel into more than 4 spatial channels, quadrupling the number of available channels and, thus, capacity.
For a CDMA system, the increase in C/I is limited (<10 dB) but, since it translates directly into an increase in capacity, it allows capacity to rise, with respect to a CDMA system with 3 sectors/cell, by a factor varying from 2 to 4, with N in the range 8 to 32.
Obviously, for both GSM and CDMA systems, the greater gain has to be paid with a higher complexity and cost of the antenna array, so that the final choice must be a trade-off between capacity, complexity and cost.

7. References

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