

ANALYSIS OF SDMA & SMART ANTENNA TECHNIQUES FOR EXISTING AND NEW MOBILE COMMUNICATION SYSTEMS

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1. INTRODUCTION

The major digital wireless cellular systems being deployed today include code division multiple access (CDMA) with IS-95, and time division multiple access (TDMA) with IS-136 and the Global System for Mobile Communications (GSM). Today's wireless communication systems are limited in performance and capacity by three major impairments:

- multipath fading
- delay spread
- co-channel interference.

In these systems, antenna arrays with spatial processing can provide substantial additional improvement. However the various types of spatial processing techniques have different advantages and disadvantages in each type of system.

With M antenna elements, such an array generally provides an increased antenna gain of M plus a diversity gain against multipath fading which depends on the correlation of the fading among the antennas. The smart antennas using fixed beams and adaptive antennas for base stations, as well as antenna technologies for handsets, can provide potential improvement including range extension, multipath diversity, interference suppression, capacity increase and data rate increase.

The Space Division Multiple Access (SDMA) technique allows us to enhance the capacity of a cellular system by exploiting spatial separation between users.

In traditional cellular systems the base station, having no information on the position of mobile units, is forced to radiate the signal in all directions, 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 [1].

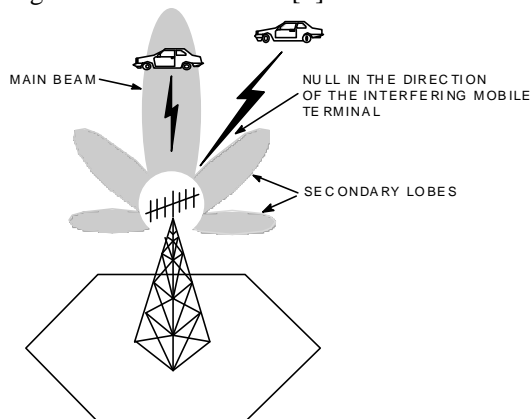


Figure 1: Radiation beam pattern adapted for a single user

These considerations have led 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" [1].

The paper is organized as follows. In Sec 2 smart antenna characteristics are presented. Sec 3 and 4 summarised SA implementation in Hybrid Fiber Radio (HFR) and Software Defined Radio (SDR) technologies respectively, while the last section contains concluding remarks.

2. SMART ANTENNA

A smart antenna refers to a group of antenna technologies that control directional antenna arrays by means of Digital Signal Processing (DSP) algorithms. A smart antenna evaluates signal conditions continuously for each signal that is transmitted or received, and then uses this information to determinate how to manipulate incoming signals to maximize performance. The smart antenna constructs a composite signal from multiple antenna arrays by optimizing signal characteristics.

The reason for using smart antennas (SA) is at least twofold. The first is to increase the system capacity by reducing interference from other users and increase the quality by reducing fading effects. In order to increase the capacity of a system (i.e. a mobile cellular system), it is possible to shape the antenna diagrams in such a manner as to receive the current user signal at maximum gain, while reducing other interfering user signals by nulling out the antenna gain in that direction. Such intelligent antenna systems utilise signal processing algorithms to automatically change the system configuration according to the current situation. In order to do so, the system must be equipped with a signal discriminator capable of distinguishing the desired signal from the interfering. The adaptive algorithm must also be stable and adaptive, normally two conditions which are difficult to satisfy simultaneously.

The second reason for using smart antennas is the classical problem of transmission in a fading channel. Antenna arrays introduce space diversity at reception, which may be exploited for equalisation. In this case, the receiving antenna is intelligent in the sense that an algorithm is implemented in order to treat the composite signal received at the different antenna elements, but this does not necessarily lead to redirection of the antenna gain as is the case for interfering users.

2.1. Smart Antenna Arrays

An antenna array consists of M identical antenna receivers, whose operation and timing is usually controlled by one central processor. The geometry of the antenna locations can vary widely, but the most common configurations are to place antennas around a circle (circular array), along a line (linear array) or in plane (planar array). The aim of the antenna array receiver is to provide acceptable error performance and maximize the Signal to Interference and Noise Ratio (SINR) for each user in the system. An antenna array containing M elements can provide a power gain of M over white noise level, but suppression of interference from other users is dependent on the form of the received data. The adaptive antenna array steers a directional beam to maximize the signal from desired user while nullifying the signals from all other directions. It is possible to use the same physical antenna elements for all channels to adapt an independent beam pattern for each channel in the system.

2.1.1. Adaptive array antenna

The adaptive array antenna picks out the desired signal amid a field of interfering signals and thermal noise and self-regulates its performance to satisfy some preassigned criteria. The adaptive array antenna creates new spatial channels, forming areas of high signal gain while reducing the effect of other signals to a minimum; and adjusts its directional beam pattern by using spatial filtering and feedback control there by maximizing the SINR.

The adaptive antenna consists of a linear or rectangular array of M homogeneous radiating elements. These elements are coupled together via some type of amplitude control and phase shifting mechanism to form a single output. The amplitude and phase control involves a set of complex weights.

The adaptive array antennas currently are often used in the reverse direction from mobile to base station only, when each signal arrives in a distinct path from an arbitrary direction. The received signal at each antenna element is comprised of the desired signal, the sum of interfering signals and thermal noise. The antenna reinforces the desired signal and suppresses the interfering signals and thermal noise by multiplying the total received signal by the set of complex weights. This requires the capability to carry out spatial filtering, which can be obtained by using, at the base station, an adaptive antenna array, whose operation is illustrated in Figure 2.

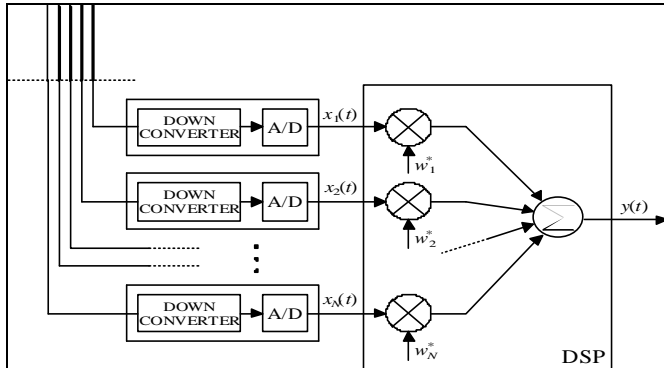


Figure 2: Structure of an adaptive antenna array in reception

The total antenna array output in direction θ_k is given as:

$$y_k(t) = \sum_{n=1}^M W_n e^{j(\omega t + \angle n k)}$$

where W_n is complex weight applied to the output of the n -th element and ω = frequency.

With adequate choice of weights, the array will accept a desired signal from direction θ_k and nullify interference signals from direction θ_k for $i \neq k$.

The antenna elements can be arranged in various geometries, with uniform line, circular and planar arrays being very common.

- The circular array geometry provides complete coverage from base station as the beam can be steered through 360°. The spacing between antenna elements is very critical in the design of antenna arrays.
- In a linear equally spaced array, grating lobes can appear in the antenna pattern if the elements are spaced more than $\lambda/2$. For an antenna array oriented along the x -axis with every array lobe that the array forms for $0 \leq \phi \leq \pi$, another lobe may also appear in $0 \leq \phi \leq \pi$. For every null formed a grating null may appear for antenna elements spacing greater than $\lambda/2$. Practically antenna element spacing is kept less than $\lambda/2$.

Another limitation of the adaptive array is that it may not be made arbitrarily small, since two closely spaced antenna elements will exhibit mutual coupling effects. The mutual coupling between two elements has several undesirable effects. In general, the minimum element spacing must be established for the particular antenna element type and array geometry. Therefore, it is advisable to maintain at least $\lambda/2$ spacing between arrays.

The maximum directivity of the array is proportional to the total length of the array by the wavelength λ , over a certain range of element spacing. The spacing between antenna elements must be large to avoid mutual coupling. The spacing between elements must be less than $\lambda/2$ to avoid grating lobes; and in a practical linear antenna array the spacing between elements is often kept close to $\lambda/2$.

Adaptive antenna array increases the cell coverage area due to antenna gain and interference rejection.

Due to improvement in Signal to Interference Ratio (SIR) the transmission bit rate is increased at the output adaptive antenna. In a noise limited environment, the minimum improvement in SIR is $10\log M$ [dB]. Adaptive antenna array technology provides likewise the flexibility that allows a reuse factor of one, that is, a single frequency can be used in all cells. In Table 1 SIR improvement versus number of adaptive antenna arrays elements is presented:

Number of antenna elements	Improvement in SIR [dB]	Required SIR [dB]
2	3	$17 - 3 = 14$
4	6	$17 - 6 = 11$
6	7.78	$17 - 7.78 = 9.22$
8	9.03	$17 - 9.03 = 7.97$
10	10	$10 = 7$

Table 1. SIR improvement of versus number of antenna elements

2.1.2. Digital Processing Techniques

All the smart antenna techniques we have encountered so far in the open literature are based on digitally implemented

baseband algorithms. Very often coefficients applied to the different elements of an antenna array have to be calculated, proposals range from matrix inversion techniques to converging digital filter algorithms reducing ISI [3]. Adaptive array techniques may be carried out both in time and frequency domain [4]. The typical software antenna (or digital beamformer) comprises a phased array, downconverters, A/D-converters and a Field Programmable Gate Array (FPGA) or DSP. The adaptive antenna will control its own pattern through feedback control. While the antenna is operating, the adjustment in amplitude and phase is performed, and either the signals are combined (maximum ratio diversity) or one of the signals is chosen (switched diversity). Figure shows a possible implementation of a maximum ratio diversity adaptive antenna system. This is a Tracking Beam Array, as opposed to the Switching Beam Array.

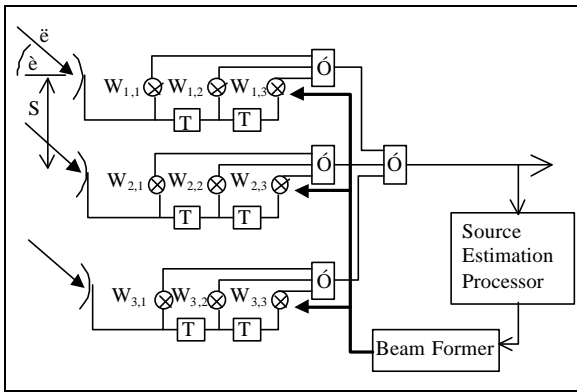


Figure 3: Example of possible implementation for smart antennas.

S , d , θ are important parameters for the optimal reception of the signals, they represent the distance between two antenna elements, the wavelength and the arrival angle of the signal, respectively. The main problem with smart antennas, is to detect the angle of arrival, θ , correctly (also called the Direction Of Arrival, DOA). The possibility of doing so will enable the Space Division Multiple Access (SDMA). Techniques based on the same principles as equalisation may be used, in [4] a technique based on an optimisation of a joint spatial and temporal Nyquist criterion has been proposed, whereas in [5], the use of a GPS antenna will assure the detection of the direction of arrival.

2.1.3. Tracking Beam Array and Switching Beam Array

As already mentioned above, there are two ways of beamforming. One method uses a fixed configuration, both in frequency and space. The switching is performed by connecting different receivers (RX) to the different antenna elements according to the algorithm. This technique is called the Switching Beam Array (SBA). The other technique consists of using configurable antennas, both in radiation direction and frequency, each antenna is connected to one single RX [3, 6]. This is the Tracking Beam Array (TBA). The latter necessitates antennas integrated with the receivers, and this is the more complex solution. The TBA may be divided in two subclasses, one called phased array, and the other called adaptive array [9]. The difference lies in the possibility of the adaptive array to correct deviations in amplitude in addition to phase correction, phase correction being the only correction possibility in a phased array. In the

case of switched diversity with antennas operation at the same frequency, it is also possible either to select the best antenna out of an array, or to optimally combine the signals received at all antennas (maximum ratio diversity). Other diversity techniques also exist, such as angle and polarisation diversity. We will present the main ideas of the two techniques TBA and SBA in the following.

The principle of the SBA receiver is shown in Figure 4. The transmitter will operate according to the same principles but in the inverse order.

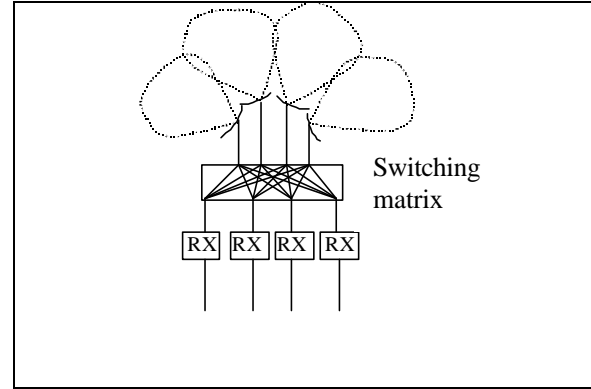


Figure 4: SA receiver based on the SBA principle.

Figure 4 does not give any indication on where to perform the RF downconversion. In the literature, propositions are given for downconversion before the switch, in the switch as well as after the switch. The preference will depend on the type of multiple access, type of switching, operating frequency and implementation complexity. In [3], the access scheme is chosen to be TDMA and the sampling is performed in connection with the switch, whereas in [6] a CDMA scheme has been supposed, the sampling is performed just after the antennas since the CDMA correlator may also be used for switching purposes. The SBA is often considered more attractive than TBA for complexity reasons. This is the case in [8], where the realisation of adaptive null steering and phased arrays are considered too complex and inadequate in the case of narrow angle of arrivals, where the signals from the mobile terminals will be strongly correlated. Hence, a SBA system is proposed and the outage probability is calculated analytically as a function of the modulation, the protection ratio, the cochannel reuse ratio, the number of antenna beams and the degree of shadowing.

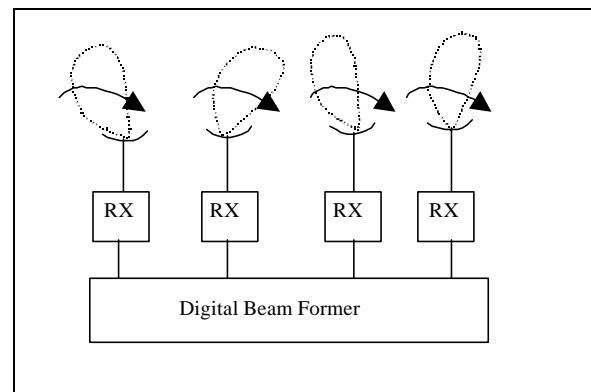


Figure 5: SA receiver based on the TBA principle.

The beams will be formed according to which user is considered user, with possible null steering in the direction of interfering users. Figure 6 shows the principles of beam

steering and null steering [3].

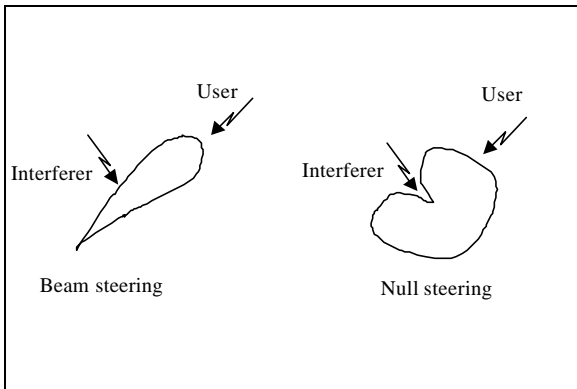


Figure 6: Illustration of beam steering and null steering.

The TBA is considered a much more complex technique than the SBA. In [6] an adaptive procedure based on Lagrange's formula is proposed. The eigenvector of the autocovariance matrix of the received signal has been shown to be approximately equal to the steering vector. The calculation of this eigenvector will give individual weight vectors for each user, hence the same number of weight vectors as there are users must be calculated.

2.1.4 Multiple Access Techniques

Various multiple access schemes may be attached to the smart antennas, both TDMA and CDMA are proposed in the literature. In the case of CDMA, the extinction of interfering user signals is an inherent property of the CDMA receiver. One limitation, which should be considered, is connected to the frequency range of the system. Above 10-20 GHz the algorithms may have problems adapting to the arriving signals, hence the implementation issues should be regarded closely. As indicated previously, the adaptive antenna system represented by TBA actually introduces a new multiple access scheme which is the SDMA. Due to different orthogonality properties, SDMA should prove better performance together with CDMA than TDMA [10].

3. SA COMBINED WITH HFR

The reasons for selecting smart antenna techniques together with HFR are the same as for other systems. It is however not evident that the reasons for selecting HFR are concordant with smart antenna technology. HFR has as a main advantage the simplification of the remote antenna unit (RAU) [11], which is the opposite philosophy of smart antenna implementation. The simplification obtained in HFR systems is acquired by conveying the radio frequency signal down a fibre directly from the antenna to a central receiver where the downconversion and signal processing takes place. In case smart antenna technology should be implemented together with HFR, the algorithmic calculation and adaptation would have to be performed at the central unit in order to be in line with the simplification argument of HFR. There should be no obstacle to this if the beamforming is achieved by digital means and not by hardware lobe forming at RF or IF. The

increase in the complexity at the remote antenna unit would thus only consist of an increased number of antennas, all the processing being taken care of by the central unit. If we consider Figures 3, 4 and 5 we may imagine that the optical fibre connection is between the antenna and the digital filter in Figure 3, between the antennas and the switch in Figure 4 and between the antennas and the RX elements in Figure 5. Actually, in Figure 4, the switch may be implemented in RF, IF or baseband, but since we have as a goal to simplify the RAU, there should be no particular reason to advise use of RF switching.

There are applications where the main reason for selecting HFR is not the simplicity of the remote antenna unit, but more connected to capacity considerations. An example would be HFR connected to satellite UMTS or terrestrial base stations with a huge amount of traffic, or covering important distances. In that case, the cost and complexity of the base station are important, downconversion and signal processing may take place in the base station, and the use of optical fibre from the base station to the central unit is there only to meet capacity or quality needs.

4. INTEGRATED SDR AND DIGITAL BEAMFORMING ARCHITECTURE FOR ADVANCED BTS

Software Defined Radio architecture can support the implementation of digital beamforming algorithms [12]. The functional block diagram of a SDR with smart antennas is shown in Figure 7. Each antenna element has its own downconverter and ADC, but the subsequent beamforming and demodulation are implemented in software and are shared among all of the elements. The addition of smart antennas to SDR base stations will require an increase in computational power, although this will depend on the nature of the beamforming and the system objectives of the antenna.

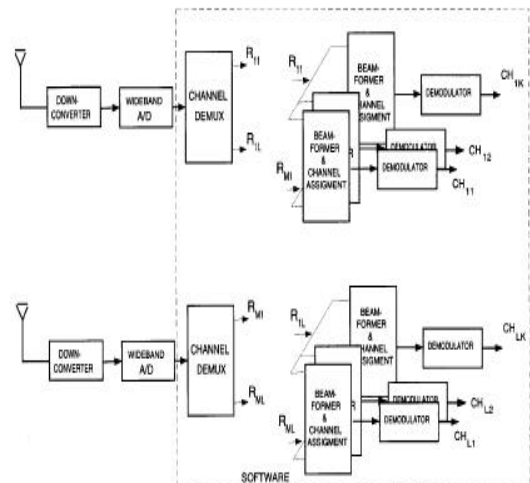


Figure 7 Functional block diagram of software radio with smart antenna

The digital hardware could be a combination of ASICs and DSPs: digital receiver may be realised by ASIC, and digital beamformer may be realised by software implemented in a DSP. Each of the resulting narrowband signals is then upconverted digitally and summed to produce a single wideband signal that is then converted back to an analog format using a high-speed D/A converter. An RF block

upconverter completes the process by translating the wideband IF back to the original cellular RF band.

5.CONCLUSIONS

Architectures with multiple antenna arrays have the advantage of offering higher gains, range extension, multipath diversity, interference suppression, capacity increase and data rate increase. Under these type of antennas the following architectures may be found: Smart antenna arrays have the ability to evaluate the signal conditions and construct a composite signal with higher performance which leads to an increase of the system capacity by reducing interference from other users and an increase to the signal quality by reducing fading effects. Adaptive antenna arrays which improve the performance of the received signal to a level that satisfies some preassigned criteria. In this architecture, the antenna reinforces the desired signal and suppresses the interfering signals and thermal noise by multiplying the total received signal by a set of complex weights. Tracking and switching beam arrays where a set of receivers are connected to the antenna arrays and by tracking the signal or switching between the best antenna, signal quality is increased. As the final remarks:

- Smart antenna systems are attractive for mobile communications because they increase the carrier to interference ratio for users, which leads to higher capacity and lower network cost.
- We have seen that SDR lends itself very well to the implementation of smart antenna systems, since both rely on baseband processing.
- HFR technology has the advantage of simplifying the antenna sites in a mobile network by shifting complexity to a central location. This is especially important for early stages of SDR deployment, where SDR equipment will be physically large and power hungry.
- Smart antenna systems will require separate HFR links for each antenna since the processing is performed centrally.

Abstract: In this paper we discuss current and future antenna technology for next generation mobile systems. Also we present the improvement that smart and adaptive antenna arrays can provide in scope of HFR and SDR systems.

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