











$h_{ij}$  is a Complex Gaussian random variable that models fading gain between the  $i_{th}$  transmit antenna and the  $j_{th}$  receive antenna

To further prove the advantage of MIMO systems over SISO systems, a diversity gain  $d$  implies that in the high SNR region, the  $P_e$  of a MIMO system decays at a rate of  $1/(\text{SNR})^d$  as opposed to  $1/\text{SNR}$  for a SISO system. From Figure 5, the maximal diversity gain  $d_{max}$  is the total number of independent signal paths that exist between the transmitter and receiver. For an  $(M_R, M_T)$  system, the total number of signal paths is  $M_R M_T$  as depicted in Figure 6.

Another reason for the widespread acceptance of MIMO technology comes from the perspective of spatial multiplexing. *Spatial multiplexing gain* is evident in a linear increase in capacity for no additional power or bandwidth expenditure and is attained by the transmission of multiple independent data signal streams to a single user on multiple spatial layers created by combinations of the available antennas. Under conducive channel conditions, such as rich scattering the receiver can separate the different streams, yielding a linear increase in capacity.

The final benefit of deploying MIMO systems is in its ability to reduce interference. Co-channel interference arises due to frequency reuse in wireless channels. When multiple antennas are used, the differentiation between the spatial signatures of the desired signal and co-channel signals can be exploited to reduce interference. Interference reduction requires knowledge of the desired signal's channel. Exact knowledge of the interferer's channel may not be necessary. Interference reduction (or avoidance) can also be implemented at the transmitter, where the goal is to minimize the interference energy sent towards the co-channel users while delivering the signal to the desired user. Interference reduction allows aggressive frequency reuse and thereby increases multi-cell capacity.

#### 4.1 Transmit Diversity Versus Spatial Multiplexing (A fundamental Trade-off)

It is not possible to exploit all the leverages of MIMO technology simultaneously due to conflicting demands on the spatial degrees of freedom (or number of antennas). The degree to which these conflicts are resolved depends upon the signaling scheme and transceiver design [6]. With the advent of MIMO, a choice needs to be made between transmit diversity techniques, which increase reliability (decrease probability of error) and spatial multiplexing techniques, which increase rate but not necessarily reliability. Applications requiring extremely high reliability seem well suited for transmit diversity techniques whereas applications that can smoothly handle loss appear better suited for spatial multiplexing. It may further appear that the SNR (signal-to noise ratio) and the degree of channel selectivity should also affect this decision. Essentially, different design criteria of MIMO communication schemes are based on exploiting the previous gains, especially the spatial diversity and multiplexing gains. Actually, both perspectives come from different ways of understanding the ever-present fading in wireless communications.

Traditionally, fading is considered as a source of randomness that makes wireless links unreliable. In response, a natural attempt is to use multiple antennas for compensating the random signal fluctuations and achieving a steady channel gain. The spatial dimension is exploited in this case to maximize diversity. Each pair of transmit and receive antennas provides a different (possibly independent) signal path from transmitter to receiver. By sending signals that carry the same information over a number of different paths, multiple independent faded replicas of the data can be obtained at the receiver end, increasing the reliability of the reception process. Some examples of MIMO schemes which fall within this category are space-time codes and orthogonal designs. A different line of thought suggests that in a MIMO channel, fading can in fact be beneficial through increasing the degrees of freedom available for communication. Essentially, if the path gains between individual transmit and receive antenna pairs fade independently, the channel matrix is well-conditioned with high probability, in which case multiple spatial channels are created. Hence, the data rate can be increased by transmitting independent information in parallel through the available spatial channels.

In fact, given a MIMO channel, both the spatial diversity and the multiplexing gains can be simultaneously obtained, but there is a tradeoff between how much of each type of gain in any MIMO scheme can extract: higher spatial multiplexing comes at the price of sacrificing diversity. The complete picture of this tradeoff was given in [7], and it focuses on the high-SNR regime and provides the fundamental tradeoff curve achievable by any scheme, where the spatial multiplexing gain is understood as the fraction of capacity attained at high SNR and the diversity gain indicates the high-SNR reliability of the system. The two previously commented design strategies correspond to the two extreme points of the curve: maximum diversity and no multiplexing gain and maximum multiplexing gain and no diversity gain. The fundamental tradeoff curve bridges the gap between these two extremes and offers insights to understand the overall resources provided by MIMO channels [8].

## 5. SMART ANTENNAS

One of the most promising techniques for increasing the capacity in cellular systems is the use of *smart* or *adaptive antennas*[2]. The technology of smart or adaptive antennas for mobile communications has received enormous interest worldwide in recent years. In actual fact, development in the Smart Antenna concept led to the present concept of Multiple Input Multiple Output (MIMO) antenna system.

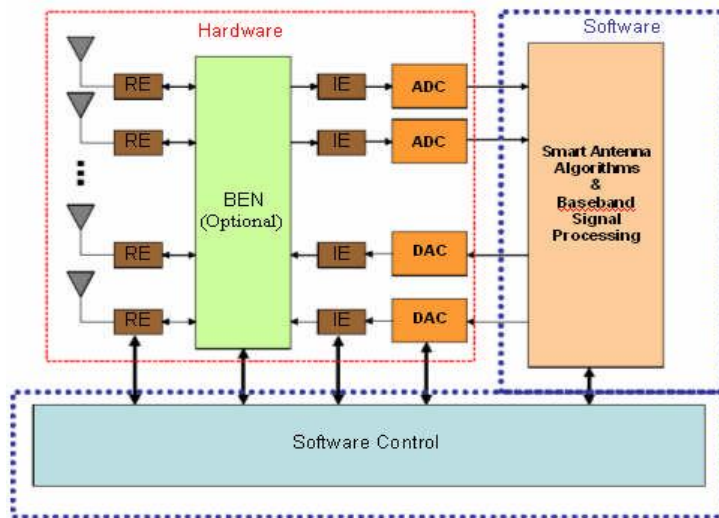


Figure 7. Block diagram of a Smart Antenna System

Prior to the present moment, base station antennas have been Omni-directional or sectored. Smart antennas are base station antennas with a pattern that is not fixed, but adapts to the current radio conditions. Smart antenna technology or adaptive antenna array technology enables the performance of the antenna to be altered to provide the performance that may be required to undertake performance under specific or changing conditions. This can be visualized as the antenna directing a beam towards the communication partner only. Smart antennas will therefore lead to a much more efficient use of the power and spectrum, increasing the useful received power as well as reducing interference. The smart antennas include signal processing capability that can perform tasks such as analysis of the direction of arrival of a signal and then the smart antenna can adapt the antenna itself using beam-forming techniques to achieve better reception, or transmission. In addition to this, the overall antenna will use some form of adaptive antenna array scheme to enable the antenna to perform is beam formation and signal direction detection. In the context of smart antennas, the term “antenna” goes beyond a radiating element to a complex system consisting of a number of radiating elements, a combining/dividing network and a control unit as shown in Figure 7. The control unit has the sole function of acting as the smart antenna’s intelligence and is normally realized using a digital signal processor (DSP). The processor controls feeder parameters of the antenna, based on several inputs, in order to optimize the communications link. With considerable levels of functionality being required within smart antennas, two main approaches or types of smart antenna technology have been developed which includes the switched beam smart antennas and the adaptive array smart antennas. The switched beam or adaptive array smart antennas are designed so that they have several fixed beam patterns. The control elements within the antenna can then select the most appropriate one for the conditions that have been detected. Although this approach does not provide complete flexibility it simplifies the design and provides sufficient level of adaptivity for many applications. Adaptive antenna arrays however allow the beam to be continually steered to any direction to allow for the maximum signal to be received and / or the nulling of any interference.

### 5.1 Smart Antenna Algorithms

Smart antennas linearly combine antenna signals into a weight vector that is used to control the beam pattern. The weights can be determined in a number of ways using different algorithms. These algorithms can be divided into three classes namely spatial reference, temporal reference, and blind algorithms. The spatial and temporal reference algorithm classes both form beam patterns and are based on linear weighting and addition of received signals at the antenna elements [9].

In Spatial reference algorithms (SR) the antenna weights are chosen based on knowledge of the array structure. These algorithms estimate the direction of arrival (DOA) of both the desired and interfering signals. The DOAs can be determined by applying different methods to the sampled data from the antenna array. The simplest way of extracting the DOAs is to use spatial Fourier transform on the signal vector. This method is limited by its resolution (size of antenna array) and has therefore limited usages. In cases where good resolution is necessary, so called high resolution methods could be used. High-resolution methods are limited only by the modeling errors and noise and not by the size of the antenna array. Common high-resolution algorithms include Minimum Variance Method (Capon's beamforming algorithm), MUSIC algorithm (determines the signal and noise subspaces and then searches the spectrum to find DOAs), ESPRIT algorithm (determines the signal subspace, from which the DOAs are determined in closed form) and SAGE algorithm (based on maximum likelihood estimation of the parameters of the impinging waves on the antenna array)[9]. When the DOAs are determined an appropriate beam pattern is created that maximizes the beam pattern in the direction of the wanted signals and places nulls in the direction of unwanted interfering signals.

Temporal reference algorithms (TR) are based on prior knowledge of the time structure of the received signals. Usually a training sequence is used as a temporal reference. The receiver aims to adjust or choose antenna weights such that the deviation of the combined signal at the output and in the known training sequence is minimized. The calculated weights are then used to form a beam pattern. The third class of algorithms termed *blind algorithms* is based on prior knowledge of the signal properties of the transmitted signal. Different algorithms can be used to determine the signal matrix for the received sample data depending on the statistical properties of transmitted signal in consideration.

## 5.2 Antenna Array Processing, Direction Finding and Beam Forming

Classical direction finding methods usually use several antennas or antenna arrays to measure phase differences while modern direction finding methods make use of all the information received on different elements of the antenna array. Before its widespread use in mobile communications, array signal processing had already found applications in radar, sonar and seismic exploration. However, next generations of wireless systems using multiple antenna arrays (or smart antennas) have brought about new technologies in the digital signal processing techniques due to their goal to intelligently enhance the desired signal and null or reduce interference.

Different algorithms for antenna array processing and direction finding has evolved as advances in Digital Signal Processing have enabled the use of new approaches for direction finding. The previous requirement for a simple and frequency-independent relationship between the signals obtained on antenna elements and the bearing no longer applies as complex mathematical relationships can be efficiently computed. High-resolution methods allow the separation of several waves arriving from different direction based on Direction of Arrival (DOA) estimation. DOA can be converted to direction relative to the true north after which the outputs of the individual antenna elements are taken to a network which contains test signal inputs and multiplexers and finally, the signals are then converted to an intermediate frequency and digitized. Conventional methods of DOA are based on the concept of beam forming which involves steering antenna array beams in all possible directions and looking for peaks in the output power. Furthermore, the antenna array signals  $u_i$  are multiplied by complex weighting factors  $w_i$  and added, a sum signal is obtained which depends on the direction of wave incidence. With conventional beam forming algorithms the phases of the weighting factors are chosen so that the weighted element signals are added in phase and thus yield a maximum sum signal for a given wave direction. This output signal is given by a weighted sum of the element input. The block diagram for the process of beam forming is shown in Figure 8.

$$y(k) = \sum_{i=1}^M w_i u_i = \mathbf{w}^H \mathbf{u}(k)$$



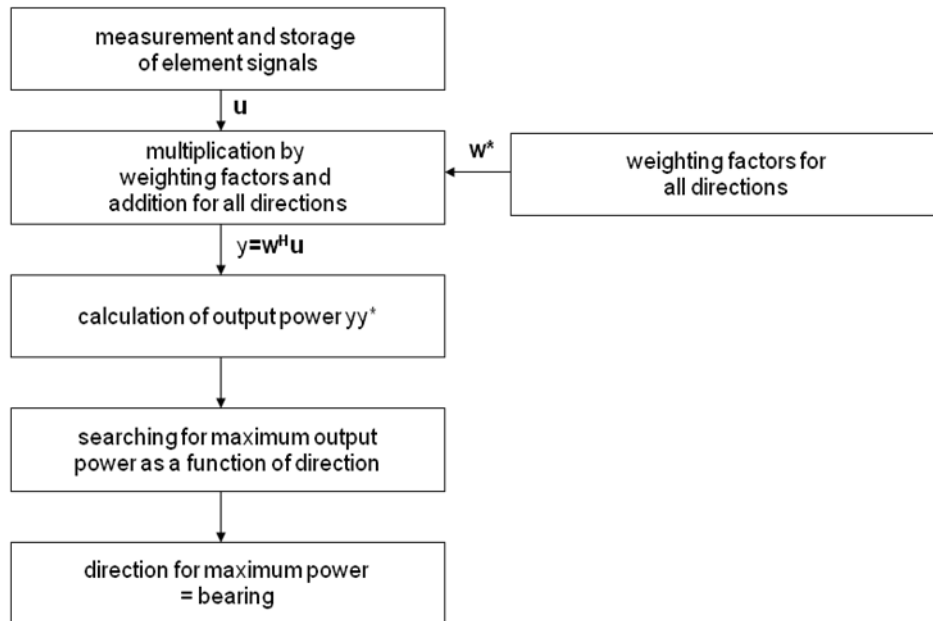


Figure 8. The process of beam forming

## 6. CHALLENGES OF UTILIZING MIMO IN COMMUNICATION SYSTEMS

The deployment of MIMO technology in systems beyond 3G (B3G) has its associated challenges or areas of concern. This can however be expected to be improved upon as the technology is continually utilized. The first challenge is that of hardware complexity which is borne out of the fact that each antenna needs a radio-frequency (RF) unit and also because a powerful digital signal processing (DSP) unit is required. Furthermore, the Software complexity is also another challenge for the designers as most signal processing algorithms are computationally intensive.

Other issues worthy of concern include an increased Power consumption evident in the reduced battery lifetime of mobile devices and the thermal energy radiated; antenna spacing challenge in order to keep the size of the mobile devices reasonable (electromagnetic mutual coupling-e.g. mobile handsets), RF interference and antenna correlation.

## 7. CONCLUSION AND FUTURE RESEARCH

The application of Multiple Antennas in telecommunication systems has helped a lot to achieve the goals of the Next Generation Networks (B3G). Despite the challenges involved, its use and success in the HSPA+ and LTE has proven that it is a technology to be reckoned with. With accompanying developments in digital modulation (especially 128-QAM) and other technologies, it can only be imagined what the future holds for users through the transformation that will follow.

However, there is still a lot of ground to be broken in this technology. Some of the areas where research is envisaged or ongoing include large MIMO (hundreds of low-power antennas (1mW) placed on a base station with potential for significant performance gains); MIMO relaying networks (combination of cooperative and MIMO technologies for increased capacity, reliability and coverage); Cognitive radio which detect ‘‘holes’’ in the expensive spectrum; Heterogeneous networks which are a combination of Macrocell with Picocell and Femtocell; Multi-cell MIMO which refers to multiple Base Station Systems each equipped with multiple antennas and development of schemes for estimation of practical impairments like timing offset, frequency offset and phase shift that need to be estimated and compensated.

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