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Chapter 1

Introductory Chapter: Smart Antennas and Beamformation

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http://dx.doi.org/10.5772/intechopen.68452

1. Introduction

Recently and over the last decade, the wireless and mobile technologies in addition to the new and improved services have grown rapidly at exponential and formidable rate. In the evolution of the modern telecommunication networks and multiple access systems, the employment of the spatial processing approaches and techniques becomes essential according to the related standards. The spatial processing is considered as the main idea behind the use of adaptive and smart antennas, antenna arrays, beamforming algorithms, interference cancelation, bandwidth-efficient signaling systems, and direction of arrival (DOA) estimation schemes (in the case of non-blind beamforming).

Smart antenna system basically consists of multiple antennas or antenna arrays and digital signal processing algorithms that are in charge of very important functions such as DOA estimation of the signals. In general, the wireless communication systems development stages can be classified based on the adopted technologies driven by the challenges of capacity demand and quality of service (QoS) requirements. These stages are summarized as follows [1]:

- Omni-directional systems: with conventional cellular structure, frequency reuse (7 cells reuse patterns), Omni-directional antenna types in the base station at the center of each cell.
- Cell splitting and sectorized systems: smaller cells (micro-cells), cell sectoring with several directional antennas in the base station.
- Smart antenna systems: with dynamic cell sectorization, multiple antennas (antenna arrays), innovative signal processing algorithms, and beamforming techniques (user location based beam assignment).

The latest telecommunication trends such as Internet-of-things (IoT) confirm the humanity willing to extend the existed technologies and employ or develop new ones which create a

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lot of new requirements and push the connectivity standards beyond the current limitations. In fact, some countries (like South Korea and the Netherlands) already had nation-wide IoT completed networks. Thus, the implementation feasibility (or readiness) of the IoT projects for smart homes, smart cities, and vehicles is very high and can be included in the proposed studies about smart antenna systems. For example, the mobile operator SK Telecom in South Korea installed and completed long range wide area network (LoRaWAN) based on long-term evolution (LTE) infrastructure (4G or 5G networks). This IoT network allows the smart devices from public and private sectors to receive and process data for different and various purposes. Thus, these cases can promote and trigger more efforts and investments directed to improve the wireless connectivity of the devices in such networks.

2. Smart antenna systems

The aforementioned smart antenna systems are widely implemented in two forms, namely, the switched beam approach where the system can choose one of many pre-defined antenna beam patterns (the antenna radiation or propagation pattern is defined as graphical representation of the power variation and radiation properties of the antenna as a function of the direction and space coordinates), and the adaptive array approach where the antenna adapts the radiation pattern beams in real time in accordance with the radio environment.

The smart antennas systems achieve higher capacity increase in comparison with the switched beam systems especially in the case of densely populated coverage areas and reduce more effectively the negative impacts of the interference. Additionally, there are more advantages that can be counted in favor of adaptive array systems such as range increasing, security enhancement (more difficult to tap any connection) [2], and location-based services improvements especially for emergency situations (spatial detection characteristics).

As in the case of any system or technology, some disadvantages or drawbacks of the smart antenna systems are found like the complexity of transmitters and receivers design, the high computation intensity with the need of powerful digital signal processors (DSPs), and the overall system employment cost.

At this point, two fundamental objectives should be performed by the signal processing algorithms of the smart antenna systems, namely:

- The DOA estimation for all incoming signals;
- Adaptive real-time calculation of the weights or coefficients that are used to steer and change the directions of the antenna array radiation beams toward the signal-of-interest (SOI) and at the same time to place nulls toward the signal-non-of-interest (SNOI) that is considered as interfering signal.

Hence, the smart antennas systems relay on the adaptive signal processing techniques such as DOA estimation and adaptive beamforming under the use of multiple antenna configurations (antenna arrays). Here, it is very useful to make some comments about the importance of antenna arrays in the development of the previous concepts.

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3. Antenna arrays

Transmit and receive diversity are effective methods for exploiting the significant benefits that are available in multiple antenna systems like multiple-input multiple-output (MIMO) wireless systems [3]. These benefits include but not limited to diversity gain (independent fading paths, channel variability reduction), array gain (average signal-to-noise ratio increase, beamforming, the gain is proportional to the array dimensions), multiplexing gain (capacity or data rate linear increase), and interference gain (aggressive frequency reuse strategy, space-time signal processing to reduce the interference effects).

It is well known that the radiation pattern generated by a single-antenna element is relatively wide with low values of directivity and gain and with less control capabilities over the important parameters. Enlarging the antenna dimensions by assembling several radiating antenna elements (array) in geometrical and electrical configurations leads to enhanced directive characteristics. The assembled antenna elements in any array can be identical (same type of antennas like dipole, micro-strip, reflector, aperture, waveguide, horn, etc.) or different. The total radiation pattern of the antenna array can be controlled and shaped using many methods such as [1]:

- The geometrical configurations (linear, planner, spherical, etc.).
- The relative distance between the elements (location and displacement).
- The amplitude and phase of the feeding electrical current for each antenna element.
- The relative radiation pattern of the individual antenna element.

The total radiation pattern of the antenna array with identical elements is obtained by pattern multiplication where the radiation pattern of a single element positioned at a reference point is multiplied by the array factor (AF). The last point can be well supported and explained by an example. Let us consider a linear antenna array with total number of identical elements equal to M with uniform spacing (d) positioned symmetrically along the same axis as shown in **Figure 1** (spherical coordinates with radial distance r, azimuth angle ϕ, and elevation or polar angle θ).

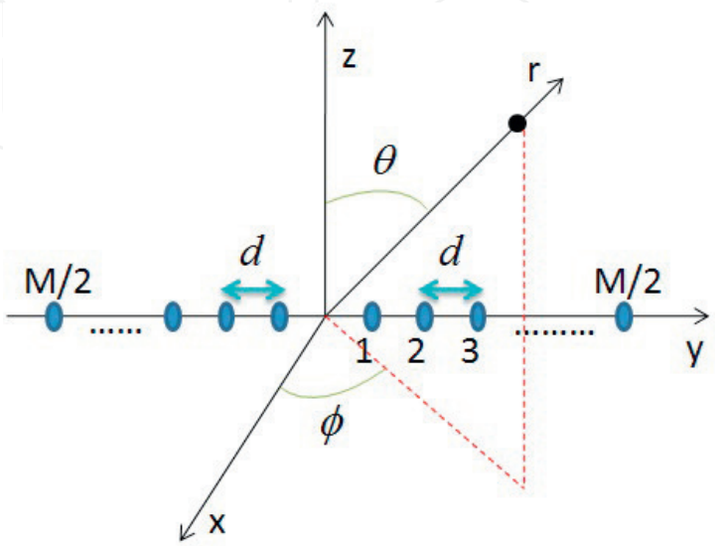


Figure 1. Linear antenna array with M identical elements.

The AF of the linear antenna array presented in **Figure 1** can be expressed using the following form [1]:

$$A F_M = \sum_{n=1}^{M/2} \omega_n \cos\left[(2n-1)\,\psi_n\right], \tag{1}$$

where ω_n is the amplitude of the feeding electrical current (excitation) for each antenna element, and ψ_n is given by

$$\psi_n = \frac{\pi d}{\lambda} \sin(\theta) \sin(\phi) + \beta_n, \tag{2}$$

where β_n is the phase of the feeding electrical current of the individual element, and λ is the wavelength (that shows the frequency relation with the AF definition). Thus, the total radiation pattern E_{total} presented by the amplitude of the electrical field of the linear antenna array in **Figure 1** is presented as:

$$E_{\text{total}} = A F_M \cdot E_{se}, \tag{3}$$

where E_{se} is the single element radiation pattern located at the array reference point. One important observation form the last discussion is that by changing the values of the AF coefficients ω_n and β_n, it is possible to control the shape of the radiation pattern plus the major to minor lobes level and the scanning capabilities of the antenna array, respectively. Obviously, any beamforming technique is able to use the previous control coefficients to shape and redirect the radiation lobes or beams in accordance with the user location. In the case of mobile communication, the planner arrays are preferred according to the three dimensions (3D space) scanning abilities.

4. Antenna beam-formation

The beam formation (BF) is a spatial signal processing technique coupled with multiple antennas (antenna array elements) that are adaptively phased to form, direct, and concentrate the beams of the radiation pattern [4]. The BF algorithms can be implemented at both transmitter side (transmit beamforming) and receiver side to provide significantly improved array gain, higher signal-to-noise ratio (SNR), and considerable reduction in co-channel interference owing to the spatial selectivity of the directional antenna array elements.

For the millimeter wave (mmWave) systems, almost all modern wireless communication networks, the antenna BF shows great benefits since highly directional adaptive antenna array elements can be designed with low profile and steering capabilities in various directions to meet and coherently align the SOIs and dampen the undesired or interfering signals (SNOIs). In **Figure 2**, a normalized radiation pattern of linear antenna array with eight identical elements ($M = 8$) and equal spacing is presented. It is shown that by employing BF technique, the major beam (main lobe) is directed toward the SOI ($\theta_1 = 30°$), and a null is placed toward the SNOI ($\theta_2 \approx 50°$).

The next figure (**Figure 3**) presents a simple adaptive BF block diagram for two-element array with spacing $d = \lambda/2$ receiving the desired signal SOI at θ_1 and the interfering signal SNOI at θ_2. This example illustrates the basic concept of null formation to satisfy certain radiation pattern requirements by BF weights (w_1, w_2) computing.

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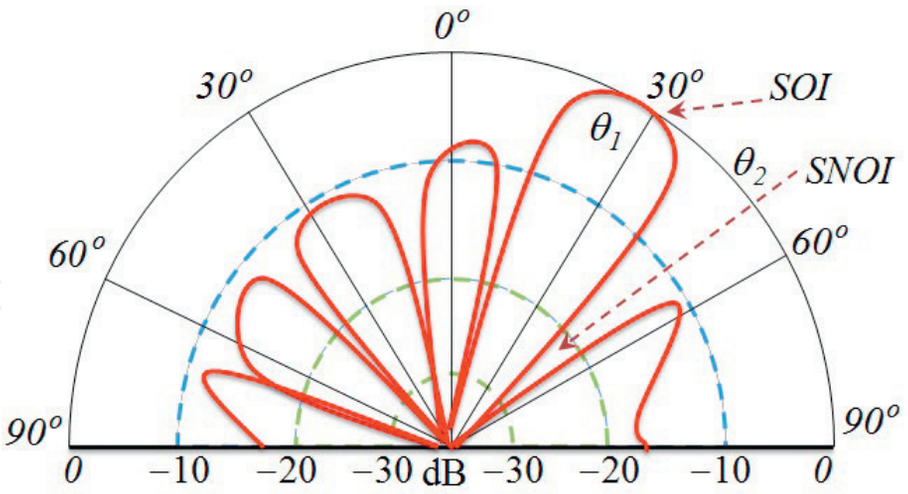


Figure 2. Antenna radiation pattern of linear antenna array with $M = 8$ identical elements and BF technique.

The BF technique in **Figure 3** should determine the complex weights w_1, w_2 to receive the desired signal $S(t)$ and cancel the interfering signal $I(t)$. Thus, the array output $y(t)$ due to the beamforming process will ideally contain the desired signal only and totally reject the interference. Solving two complex equations, the optimum complex weights w_1, w_2 are defined to achieve the maximum signal-to-interference ratio (SIR). In practice, and under non-stationary signal condition and non-homogeneous noise, the BF complex weights are computed with adaptive algorithms.

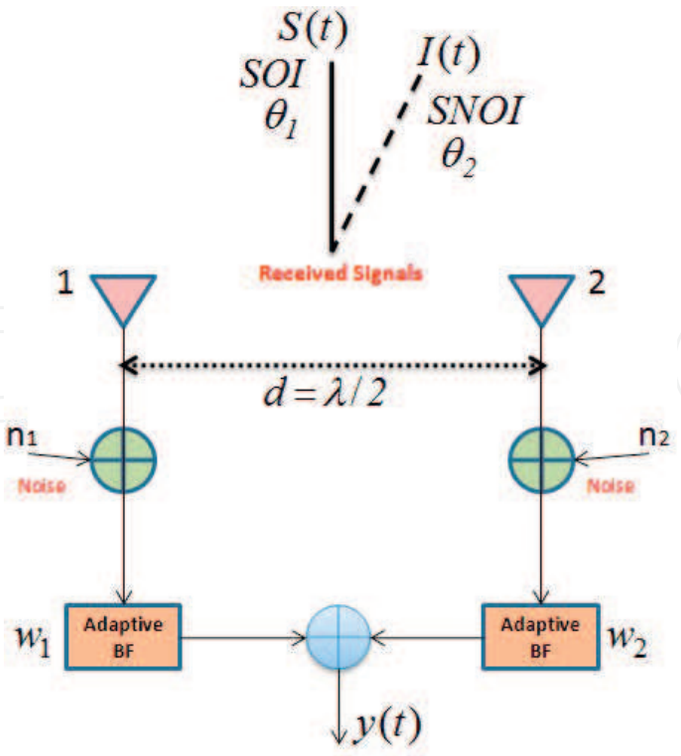


Figure 3. Antenna BF block diagram.

Some kind of adaptive beamforming algorithms do not need the information supplied by the DOA estimation as in the case of DOA-based adaptive beamforming algorithms (non-blind beamforming). Instead, these algorithms (blind) uses reference signals or training sequences (codes) in order to adjust the amplitude and phase coefficients (ω_n, β_n) of the antenna array factor (AF) [5]. A common set of predefined BF codes can be found in the related standard (IEEE 802.15.3c).

In wireless communication sector, the adaptive BF weights are chosen to maximize the quality of communication channel (or the quality of the received signal). Some commonly used adaptive BF approaches can be mentioned:

- Minimum mean-square-error (MMSE) approach: the complex weights are defined in order to minimize the mean square error between the beamformer output and the expected signal (using Wiener filter) [6].
- Least mean square (LMS) approach: very simple and effective algorithm that minimizes the mean squared error (MSE) cost function and computes the BF weights using iterative and bounded conditions.
- Maximum SIR approach: the complex weights are determine to maximize the SIR value (desired signal and interference strengths are estimated by the receiver).
- Minimum variance approach: the complex weights are computed to minimize the noise variance at the beamformer output (the signal waveform and DOA are known).

The beam-space adaptive beamforming (beam-space transformation) employed in communication systems uses fast Fourier transform (FFT) beamforming where a set of FFT outputs can be combined using complex weights and sums to form arbitrary radiation patterns (baseband signals are combined from different antenna elements) [7].

5. DOA estimation

In some other references, the DOA estimation is called angle of arrival (AoA) or angle of departure (AoD) estimation. The ability to measure the DOA of a wireless signal with higher resolution in comparison with the antenna beam width is defined as super resolution. The type of beamformers that needs DOA estimation is called non-blind BF techniques. When the antenna array elements receive the incoming signals from all directions, the DOA technique estimates these directions based on the time delay and array geometry concepts. To understand these concepts, the two elements antenna array in **Figure 4** can help to simplify and derive the DOA estimation.

The arrival time difference Δt of the signal at the two antenna elements (assuming that the signal is direct from the source or we have a plan wave) can be given by

$$\Delta t = t_2 - t_1 = \frac{d\cos\theta}{c} \tag{4}$$

where c is the speed of light in the free space. Clearly, the DOA demonstrated by the angle θ can be determined knowing the spacing d between the array elements (by design) and the time delay Δt. This method is very sensitive to signal reflections (multipath problem) and to the existence of interfering signals.

The DOA estimation algorithms are classified based on the data analysis into four different groups:

- Conventional algorithms: the estimation process is based on beamforming and null steering without the exploiting of the received signal statistics such as delay-and-sum method and Capon's minimum variance method.
- Sub-space based algorithms: the method utilizes the received signal structure to improve the resolution such as multiple signal classification (MUSIC) and the estimation of signal parameters via rational invariance technique (ESPRIT) [1].
- Maximum likelihood (ML) algorithms: the estimation is obviously optimal based on the maximum likelihood sense where the DOA algorithm maximizes the likelihood that the signal arrived from a particular direction [8]. The ML algorithm outperforms the sub-space–based techniques under low SNR and spatially correlated signal conditions, but it is computationally intensive.
- Integrated algorithms: the property restoral method and the sub-space–based approach are combined in order to separate multiple signals and estimate their spatial signatures prior to the DOA estimation (mainly performed by sub-space based algorithm).

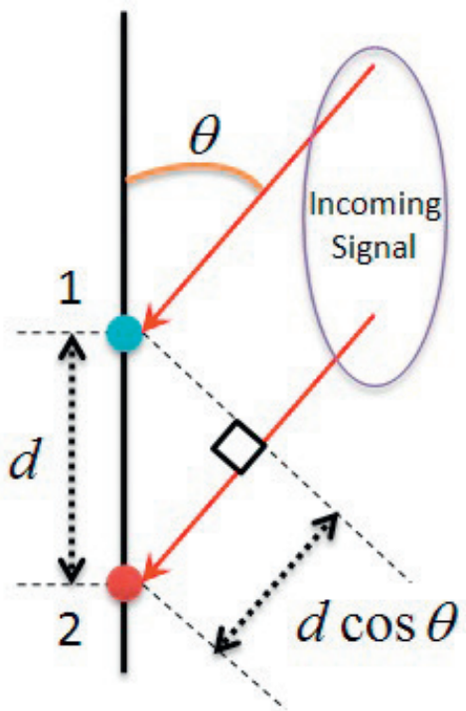


Figure 4. DOA estimation main concept.

Since the DOA is a parameter estimated from received data, the Cramer-Rao lower bound (CRLB) can be used to define the minimum variance of this estimation [9]. The CRLB defines the best performance obtained after minimizing the residual noise in unbiased estimates (noisy data defiantly produce noisy estimates). Thus, the determination of the CRLB for any DOA algorithm is helpful to find the theoretical limits for performance evaluation.

6. Beam-formation performance remarks

Two-dimension linear antenna array pattern with 10 elements is demonstrated in **Figure 5** in the case of LMS beamforming algorithm. In this scenario, the antenna array receives two SOIs at $\theta_1 = 0°; 10°$ and two SNOIs at $\theta_2 = 30°; -40°$ where the SNR = 5[dB] and the interference-to-noise ratio is equal to INR = 10[dB] (the interference is more severe problem comparing with the noise).

It is noticeable that the radiation pattern generated by the antenna array elements and LMS algorithm has its maximum toward the SOIs directions while the nulls (minimum power) are placed toward SNOIs directions.

The time-varying multipath channel (fading channel) is a common model used for wireless communication networks. The spatial diversity techniques (replicate the transmitted information over independent channels using different antennas) form an effective solution to combat the negative influence, presented by performance degradation, of the fading channels. Any BF approach can be combined with spatial diversity to improve and enhance the performance of the wireless transmission. The performance simulations given in **Figure 6** are made in the case of Rayleigh fading channel model and for transmit diversity scheme (two antennas) with and without BF. The bit error rate (BER) as a function of energy per bit E_b to noise spectral density N_0 ratio (similar to SNR) is presented for binary phase shift keying (BPSK) modulation with hard decision receiver.

The results shown in **Figure 6** indicate that the BER is less using BF (LMS algorithm) in comparison with the case when the BF is not employed over the whole E_b/N_0 range. Thus, the BF technique could boost and improve the receiver performance by reducing the BER value.

The appropriate utilization of the channel state information (CSI) sent over the feedback link to the transmitter side helps to achieve the highest performance from any MIMO or antenna array system. The beam training (alternative solution of the conventional feedback) is employed to configure transmit and receive BF vectors where the transmitter sends information over several beams and uses the feedback from the receiver to find the beast beam (IEEE 802.11ad) [4]. New approaches have been developed for closed-loop spatial multiplexing based on the beam training and feedback combination such as code-book BF, BF with weight optimization based on AoD estimation, and long-term BF [4].

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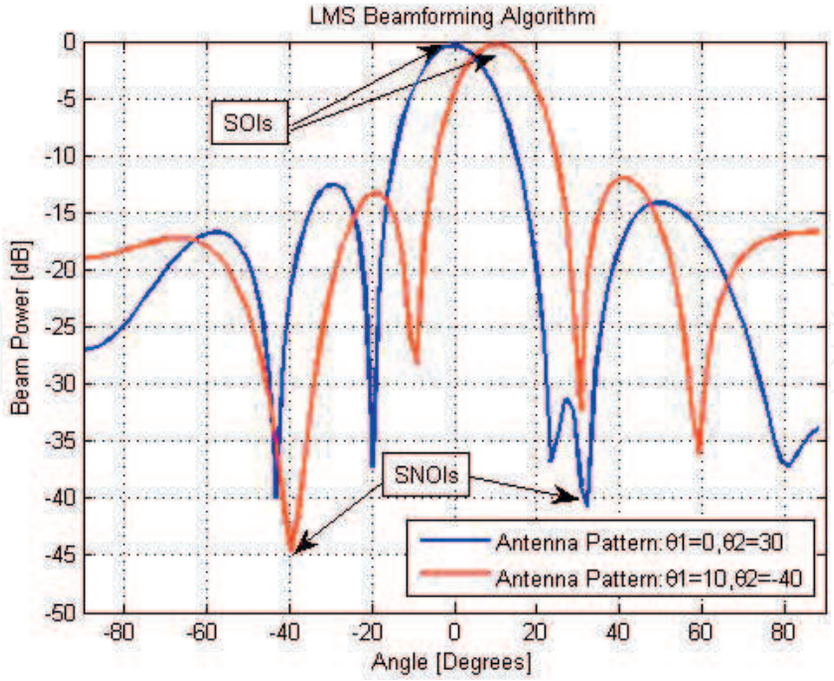


Figure 5. 2D antenna array pattern of 10 elements applying LMS-BF algorithm.

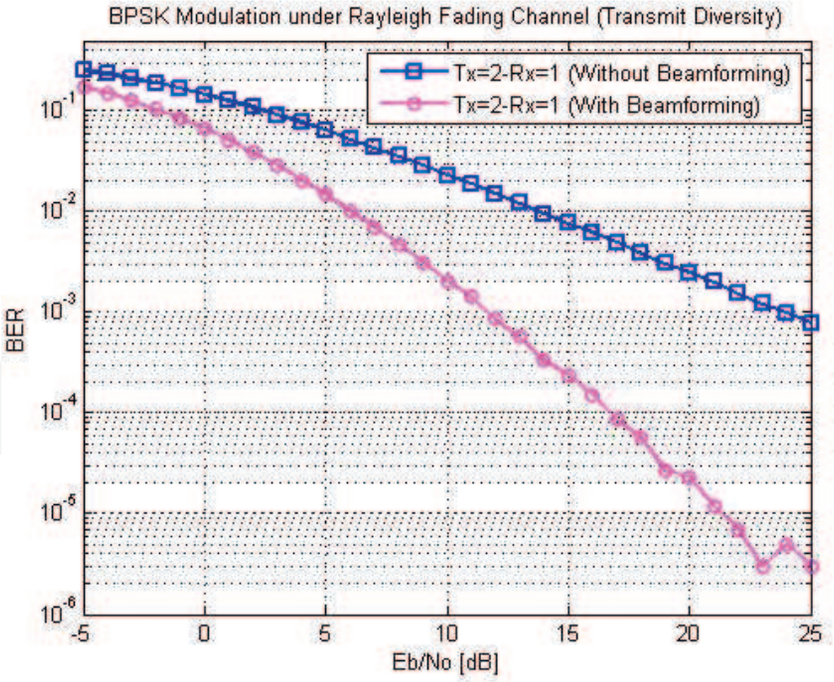


Figure 6. BER over Rayleigh fading channel with and without BF.

The basic concepts and the importance of smart antennas, BF, and DOA estimation are addressed in this chapter. The book focuses on the latest contributions made by researches and experts on smart antennas and beam-formation approaches in order to present the recent advances on the field.

Acknowledgements

This work is performed by Radio Physics Research Group (RPRG) at Polytechnic University of San Luis Potosi (UPSLP) and supported by the National Council of Science and Technology in Mexico (Consejo Nacional de Ciencia y Tecnología CONACYT, Mexico).

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