Appendix - A Survey of Spatial Channel Sounders based upon Virtual, Real and Beamforming Antenna Arrays

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Abstract

Since the advent of MIMO wireless technology in the late 1990's, there has been much progress in developing experimental techniques for characterizing the spatial distribution of scatterers that contribute to multipath propagation and the multiplicity of directions from which signals depart the transmitter and arrive at the receiver. Researchers have shown great ingenuity in devising array configurations, measurement setups and signal processing algorithms that reveal the spatial channel. In this survey, we identify the most important contributions to this field and summarize the current state of the art. In certain cases, we compare and contrast the requirements of a channel sounder operating in the 2 GHz band and one that operates in millimetre-wave bands.

Introduction

Utilization of smart antennas exploiting the directional behavior of the mobile radio channel has raised significant interest in cellular mobile communication systems in recent years. Smart antennas dynamically boost gain in the direction of strong signal and steer nulls towards sources of interference. A base station equipped with this technology will be able to not only determine whether the mobile station is located within the cell (sector), but also direct its communication towards the exact location of the mobile station; similarly, a mobile station with smart antennas will be able to favor the desired base station over the interfering ones; leading to obvious increases in capacity and quality of service as a result of diversity gain, source separation, interference reduction, and joint space-time equalization.

Use of this powerful technique requires highly directional arrays of antennas and extensive knowledge about the spatial radio propagation channel, including not only the conventional properties of the wireless channel studied in classical models, but also the directional spreading at the antenna sites, i.e., estimation of the time-varying Directions of Arrival (DoA) and Directions of Departure (DoD) associated with the propagation paths. Towards this end, different geometry-based or spatial-stochastic channel modelling approaches have been developed [6], allowing parameterization and characterization of the spatial channel in theoretical terms; however, the complex nature of the channel which is mainly due to time variance and multipath, imposes that these approaches be simplified to a great extent [13],[24]. This fact is not favorable in cases where an accurate channel model directly impacts the capacity of the system. Specifically, since it has repeatedly been shown that the wireless propagation channel has a key impact on both the information-theoretical limits and the performance of practical MIMO systems [7]. Consequently, there have been increasing inclinations towards measurement-based channel modelling techniques or equivalently, spatial channel sounding, which allow realistic parameterization of the spatial channel, could serve as a validation benchmark for the theoretical models, and provide further input for channel modelling in general.

Estimation of the Direction of Arrival (DoA) and Direction of Departure (DoD)

In a MIMO radio channel sounder, multiple antennas are used in the transmitter side as well as the receiver side, an excitation signal (usually a PRBS signal, otherwise referred to as Pseudo-Random Noise) is sent through the channel, and upon measuring the channel response between each pair of antennas at both sides and post-processing the received signal using space-time signal processing algorithms, the vector channel response matrix is determined. In part, characterization of the directional nature of the spatial channel translates to incorporating the Direction of Arrival (DoA) and Direction of Departure (DoD) statistics to obtain accurate knowledge of the multipath phenomenon and possible uncovering of each of the scatterers' locations, which would be vital to the smart antenna systems. Towards this end, signal processing aspects of the smart antennas have concentrated on the development of efficient algorithms for DoA and DoD estimation and adaptive beamforming, a number of which are presented and analyzed in this survey.

Use of Antenna Arrays for High Resolution DoA Estimation

In addition to high resolution space-time signal processing algorithms, sophisticated antenna array architecture design, along with mechanically and electrically stable construction and precise calibration is required to achieve high DoD/DoA resolution. To change the beam direction of an array when transmitting, a beamformer controls the phase and relative amplitude of the signal at each element in the array, in order to create a pattern of constructive and destructive interference in the wavefront. When receiving, information from different sensors is combined in a way that the expected pattern of radiation is preferentially observed. Antenna arrays employed in the channel sounder essentially provide a means for 'sampling' the channel impulse response in space [8] and consequently, each particular set of antenna arrays together with its associated signal processing unit, is able to measure the channel impulse response to a certain 'resolution'. In cases where the radio channel is variable in time and space to a high extent such as industrial, road traffic, and complex urban scenarios, derivation of DOAs and DODs of multipath calls for sophisticated arrays and high-resolution parameter estimation algorithms, such as multiple signal classification (MUSIC) and the estimation of signal parameters via rotation invariance technique (ESPRIT). Incorporation of a desirable configuration of real or synthetic arrays with an accurate, compatible, and efficient signal processing algorithm is the key factor in design and implementation of a high resolution spatial channel sounder and is therefore a main subject of study in this paper.

Double-Directional Channel Sounding

Before the introduction of the double-directional channel model in 2001 [1], signal processing schemes for this means concentrated on the development of efficient direction-of-arrival (DoA) estimation techniques based on implying directionality at one end of the radio link and deriving a representation based on the antenna type used in the other end. However, a high resolution double directional radio channel model which is independent of the antenna types would be invaluable in parameterizing the spatial channel. In double-directional channel sounding, the goal is to jointly estimate the wave vectors (including the polarization) in both transmitter and receiver ends of the radio link. With its high resolution, the double directional concept will provide accurate estimates of the channel's multipath richness, which is the most important parameter for the capacity of MIMO channels. This concept, along with its representative implementations, is thus further surveyed in this paper.

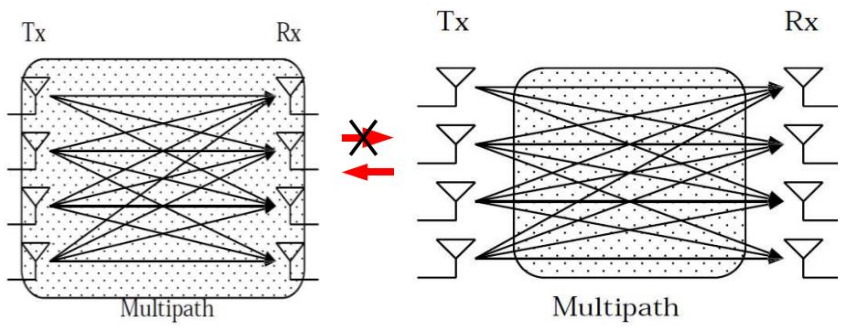


Figure 1- the double-directional structure of the MIMO channel (right) as opposed to a non-double-directional representation (left). Specifically, double-directional measurements that include joint DoA/DoD estimation allow the separation of the directional dependent influence of the measurement antennas from the channel measurements which is a prerequisite of antenna-independent channel characterization.

Short Summary of UBC Radio Science Lab's Channel Sounders

The Radio Science Lab at UBC conducts a variety of propagation measurements with supports from industry sponsors. Here we present a brief summary of the channel sounder implementations for RSL's two main ongoing projects, the Huawei and Siradel projects.

- *Huawei Project*

The Huawei project is mainly concerned with channel measurements at 28 to 38 GHz in the context of system design for the emerging 5th Generation wireless cellular access. Specifically, since this project does not assume MIMO operation and is rather concerned with investigating the nature of the wireless channel in Millimeter-wave frequency bands per se, the channel parameters of interest are the Power Delay Profile (PDP), coherence bandwidth, delay spread, and the angles of arrival and departure (AoA and AoD). For this purpose, RSL is using a stepping correlator channel sounder with Rubidium Frequency Standards, offering the advantage of long distance measurements without using cables for TX-RX synchronization. The transmitter outputs a Binary Phase-Shift Keying (BPSK) modulated pseudorandom noise (PN) sequence, triggered once per second by a GPS using a Vector Signal Generator. Automated and controlled by a MATLAB script, the receiver captures the IQ data using the VSA software and processes the captured data in real time to compute the channel's power delay profile and delay spread. Both Huawei and Siradel projects require outdoor measurements in a 500 meter radius that resembles typical urban environments. The field measurements are therefore conducted in UBC Vancouver campus.

- *Siradel Project*

The same stepping correlator channel sounder system would be able to characterize dual-polarized Multiple Input Multiple Output (MIMO) channels for Long-Term Evolution (LTE) applications, as required by the terms of the Siradel project. This project involves wide-band polarimetric outdoor macrocellular channel measurements at 2 GHz with the Short Pulse technique using a $1 \times N$ linear array at the transmitter and an $M \times M$ synthesized array at the receiver. A suitable choice of the antenna to be used in the arrays is the 1.9 GHz dual-polarized linear patch antenna. Two orthogonal dual-polarized Pseudo Random Noise sequences are generated via a vector signal generator at the TX, which is capable of high speed toggling between the polarizations using an RF switch. These sequences are captured in the RX, consisting of a Velmex bi-slider realizing a virtual array, and prospectively processed using the ESPRIT algorithm to obtain the AoA and AoD information. The process is automated through a LabView interface, although a MATLAB script has also been developed for establishing communication between the devices.

Objectives and Outline of This Survey

This appendix aims at summarizing briefly the current state of the art in DoA estimation, and beamforming array implementation techniques for MIMO vector channel sounding that may be relevant to UBC RSL's Siradel project. Specifically, we will try to identify the current trends and milestones in the field, and present a general idea of the gaps or limitations in the current work that might be resolved through future research.

The appendix is organized as follows: Sec. 1 presents a review of algorithms for estimating the Direction of Arrival and discusses two of the most popular high resolution algorithms, MUSIC and ESPRT in more detail. A comparison between the performances of the high resolution algorithms is further presented in Section 1. Section 2 discusses a review of different antenna array types for beamforming in high resolution MIMO channel characterization, including planar and spherical arrays, and presents an overview of the pros and cons of each. A brief discussion and survey on double directional channel sounding using virtual arrays is presented in Section 3. Finally, a number of suspected limitations of the current research work have been presented in Section 4, along with recommendations to RSL for improvements in their implementation of the Siradel project's MIMO channel sounder system.

1. Review of Algorithms for Estimating the Direction of Arrival

This section briefly discusses methods and algorithms used in estimating the direction of arrival (DoA) of a radio signal impinging on an array of antennas. In practice, the problem of DoA estimation, which may be treated as equivalent to that of spectral estimation, is made difficult by the fact that there is usually an unknown number of signals impinging on the array simultaneously, each from unknown directions and with unknown amplitudes. Also, the received signals are always corrupted by noise [16]. Nevertheless, this problem has been intensively studied for a long period and many DoA estimation algorithms have been proposed. In a general sense, array-based estimation techniques for directional of arrival can be divided into four categories: conventional methods, subspace-based methods, maximum likelihood methods, and the integrated methods combining the subspace-based techniques with property restoral techniques [8]. This section will introduce the conventional methods and subsequently, will further elaborate on two most popular subspace-based methods; namely, MUSIC and ESPRIT.

1.1. Conventional Methods

Conventional methods are based on classical beam forming principles; that is, given a certain structure of an array of antennas, these methods try to steer the beam electronically in every possible direction, just as it can be steered mechanically, and seek the direction of the maximum received power by looking for the peak of the output power. They do not base their assumptions on the statistical properties of signal and noise, nor do they make use of the nature of the narrowband data model of the received signal vector. These methods thus require a large number of elements to achieve high angular resolution and their resolution is highly dependent on the physical size of the array aperture. Examples of conventional methods include Capon's Minimum Variance method and the Delay and Sum (Bartlett) method. The Minimum Variance method takes into account uncertainties or variations associated with the array response, presumably due to errors in AoA estimation or uncertainty in the array manifold. It then chooses the weights such that the weighted array power output is minimized subject to a unity gain constraint in the desired look direction. The downside to this method is that small variations in the array manifold can greatly and adversely affect its performance. On the other hand, the Delay and Sum method exploits the fact that there are different delays associated with signals impinging on the array from different directions and the output power is maximized when the signals originate from the same direction, due to the fact that they are more correlated and thus add constructively. This method has many disadvantages, among which is the poor angular resolution associated with beam width limitations, as this method does not distinguish delay differences less than the sampling period.

1.2. High Resolution Methods

In spite of the fact that the conventional beam forming methods are often successful and widely used, they still suffer from lack of resolution, which in most cases is due to the fact that these methods do not consider or exploit the structure of the data model. Schmidt [34] was the first to develop a scheme with higher resolution using a more accurate data model for the case of sensor arrays of arbitrary form. His proposed technique is the so-called MUSIC (Multiple SIgnal Classification) algorithm, which is a high resolution technique based on exploiting the eigen structure of the input covariance matrix. This method further assumes that the noises embedded in each signal source are uncorrelated, and hence the correlation matrix is diagonal. SAGE (Space Alternating Generalized Expectation Maximization [33], is another sub-space-based method which supports joint estimation of DOA and DOD using complex radiation patterns of antennas as the inputs for estimation. However, its convergence is not guaranteed in complicated propagation environments, array calibration is a major problem in this method and also it is more sensitive to noise than beam forming. The MUSIC algorithm, along with another algorithm called the EStimation of Rotational Parameters via Rotational Invariance Technique (ESPRIT), formed the core of a whole new class of DoA estimation methods called subspace-based methods. Basics of the MUSIC and ESPRIT methods are discussed hereinafter.

1.2.1. MUSIC

The MUSIC algorithm is a high resolution signal parameter estimation algorithm which is able to provide information about the number of incident signals, the Direction of Arrival (DoA) of each signal, noise power, cross correlations between each pair of incident signals etc. This algorithm decomposes the autocorrelation matrix into signal subspace and noise subspace and uses the orthogonality between the two complementary subspaces to estimate the DoAs. While this algorithm is of very high resolution and is adaptive to the shape of the antenna array, it requires exact calibration of the antenna array. This point is further stressed in section 1.3.

In order to demonstrate the algorithm, assuming that K far-field stationary and narrowband signals impinge, in a linear sum fashion, on an array of M sensors from direction angles $\boldsymbol{\theta} = [\theta_1, \theta_2, \ldots, \theta_K]$ which is corrupted by additive circular complex Gaussian white noise. The received signal at the array output can be expressed as

$$X(t) = \sum_{k=1}^{K} \boldsymbol{a}(\theta_k) s_k(t) + \boldsymbol{n}(t) ,$$

where $s = [s_1 \; s_2 \; s_3 \ldots s_K]$ is the zero-mean vector of the incident signals, $\boldsymbol{n}(t)$ is the noise vector with zero mean and covariance matrix $\sigma_n^2 \boldsymbol{I}_{\boldsymbol{M}}$**,** and $\boldsymbol{A}(\theta)$ is the array steering vector corresponding to the directions of arrival.

The array covariance matrix is then given by

$$R = E[X(t) X^H(t)] = \boldsymbol{A R_{ss} A^H} + \sigma_n^2 \boldsymbol{I}_M ,$$

where $[\,]^H$ denotes conjugation.

$\boldsymbol{R_{ss}}$ has K eigen vectors corresponding to the signal subspace and $M - K$ eigen vectors associated with the noise subspace. We can thus construct the $M \times (M - K)$ subspace spanned by the noise eigen vectors as

$$V_N = [V_1 \;\; V_2 \;\; V_3 \;\; \ldots \;\; V_{M-K}] .$$

It can be shown that the noise subspace eigen vectors are orthogonal to the array steering vectors at the angles of arrival $\theta_1, \theta_2, \ldots, \theta_K$ and the MUSIC pseudo-spectrum is thus given by

$$P_{MUSIC}(\theta) = \frac{1}{\boldsymbol{a^H}(\theta) V_N V_N^H \boldsymbol{a}(\theta)} .$$

The above equation is a measure of the closeness of the array manifold to the signal subspace. Since the product $V_N V_N^H$ represents projection on the noise subspace, the denominator in the above equation is a measure of the distance between the array's steering vector $\boldsymbol{a}(\theta)$ and the estimated noise subspace V_N. The more the two vectors are orthogonal, the less will the denominator become, giving rise to peaks in the MUSIC pseudo-spectrum. The K largest peaks in the spectrum will correspond to the actual directions of arrival $\theta_1, \theta_2, \ldots, \theta_K$.

Various modifications to the MUSIC algorithm have been proposed to increase its resolution performance and decrease the computational complexity. One such improvement is the Root-MUSIC algorithm developed by Barbell [35], which is based on polynomial rooting and provides higher resolution, but is applicable only to a uniform spaced linear array. [33] CYCLIC MUSIC which exploits the spectral coherence properties of the signal to improve the performance of the conventional MUSIC algorithm has been also proposed [36]. Fast Subspace Decomposition techniques have also been studied to decrease the computational complexity of MUSIC [37].

1.2.2. ESPRIT

The ESPRIT algorithm is another subspace-based scheme developed by Roy et al. [17] which, not only is more efficient than MUSIC in terms of computational burden (since it does not involve an exhaustive search among all possible steering vectors), but also does not place stringent requirements on array calibration (since it does not require that the array manifold be precisely known). ESPRIT derives its advantage by exploiting the rotational invariance property in the signal subspace which is created by two arrays with a structure that is invariant to translation. That is, it assumes an array composed of two identical sub-arrays (matched pairs or doublets) separated from one another by a fixed distance, denoted from now on by d.

Assuming that there are $K < M$ narrowband sources centered at the frequency f_0, the signal induced on each subarray is given by

$$x_1(t) = \boldsymbol{A}s(t) + \boldsymbol{n_1}(t) \text{ and}$$

$$x_2(t) = \boldsymbol{A\Phi s}(t) + \boldsymbol{n_2}(t) \text{ ,}$$

where $\Phi = diag(e^{jkdsin(\theta_1)} \quad e^{jkdsin(\theta_2)} \quad \dots \quad e^{jkdsin(\theta_K)})$ is a diagonal matrix whose elements represent the phase delays between the doublet sensors. Basically, ESPRIT exploits the rotational invariance of the signal subspace induced by the translational invariance of the sensor array.

Creating the signal subspace for the two subarrays results in two matrices V_1 and V_2. Since the arrays are related to each other by translation, the subspaces of eigenvectors are related by a unique nonsingular transformation matrix Ψ such that $V_1\Psi = V_2$. There must also exist a unique nonsingular transformation matrix T such that $V_1 = AT$ and $V_2 = A\Phi T$, so that we can finally derive

$$T\Psi T^{-1} = \Phi \ .$$

Therefore, the eigenvalues of Ψ must be equal to the diagonal elements of Φ such that

$$\lambda_1 = e^{jkdsin(\theta_1)}, \quad \lambda_2 = e^{jkdsin(\theta_2)}, \quad \ldots \quad , \quad \lambda_K = e^{jkdsin(\theta_K)}$$

Once the eigen values of Ψ are calculated, the angles of arrival are estimated as $\theta_i = \sin^{-1}\left(\frac{\arg(\lambda_i)}{kd}\right)$.

1.3. Performance Comparison of high resolution DoA estimation algorithms

Here we present a brief comparison of how well the aforementioned methods perform in terms of a number of criteria; namely, the number of resolvable signals, whether the method addresses coherent signals, accuracy, resolution, need for calibration, computational efficiency, and whether the algorithm can be implemented in multidimensional arrays.

Number of Resolvable Signals: In MUSIC we assumed that the number of elements, M, was greater than the number of signals, K. This is required because MUSIC depends on the existence of a noise subspace. Therefore with M elements, MUSIC can resolve a maximum of $(K - 1)$ signals. In ESPRIT, a similar argument holds.

Addressing Coherent Signals: coherent signals are defined as signals with high correlation. While MUSIC fails to treat these kinds of signals, ESPRIT and Root-MUSIC have overcome this problem.

Accuracy: all the adaptive techniques have demonstrated similar accuracies in determining angles of arrival [16], while MUSIC slightly outperforms ESPRIT in this sense. The accuracy of all the methods can be increased by increasing the number of the array elements, increasing the signal to noise ratio, and increasing the number of samples.

Resolution: For MUSIC, the ability to resolve a scenario in which the impinging signals are closely separated in angles of arrival depends on the signal to noise ratio at the input of the array and the total number of samples of data (proportional to the observation interval) used to compute the MUSIC spectrum [8]. Furthermore, the resolution also depends on the number of elements in the array, while ESPRIT does not exhibit this problem.

Sensitivity to Calibration: as mentioned before, errors in array element spacing and calibration measurements for the steering vectors will lead to distortions in the MUSIC spectrum [8].

Computational Efficiency: as discussed previously, ESPRIT eliminates the exhaustive spectral search procedure inherent in MUSIC by exploiting the eigen value decomposition approach, and therefore drastically reduces the computational burden. Also, the Root-MUSIC algorithm enjoys a substantially reduced computational complexity and an improved threshold estimation performance as compared to MUSIC [32].

Implementation in Multidimensional Arrays: It has been proven that MUSIC and ESPRIT are both convenient and reliable for use in two dimensional DoA estimation. However, Root-MUSIC is only applicable to uniform linear arrays (ULA) or non-uniform linear arrays whose sensors are restricted to lie on a uniform grid [38]. According to the simulation results of [39], the MUSIC algorithm shows slightly better performance than ESPRIT in the two dimensional case, and for both algorithms, the Root Mean Square Error of the azimuth angles are smaller than those of the elevation angles.

2. Review of Different Beamforming Antenna Array Architectures for MIMO Channel Sounding

The spatial features of the MIMO channel response are captured by antenna arrays. An array is a configuration of multiple antenna elements arranged and interconnected in space to obtain a directional radiation pattern. It is possible, using phased antenna arrays, to electronically scan the main beam and place nulls in any direction by changing the phase of the exciting currents in each of the antenna elements. It is also possible, through antenna arrays, to obtain high resolution measures of the directional spreading of the MIMO channel at the transmitter and receiver sides.
Sophisticated antenna architecture design is required to achieve high DoD/DoA resolution in MIMO channel sounding. This has to be developed with mechanically and electrically stable construction and precise calibration. Since there is always a tradeoff between various specifications including resolution, measurement time, availability and costs, there is a wide variety of useful antenna array architectures. In the following, we summarize some design architectures and considerations.

2.1. Antenna Array Configurations

2.1.1. Uniform Linear Array (ULA)

The classical uniform linear arrays consist of M elements placed linearly with uniform spacing. Due to their simplicity and applicability to many DoA estimation algorithms, ULA's are widely used in array designs; however, one of the biggest drawbacks of the uniform linear array is that it can only resolve the azimuthal angle of the impinging waves, and is thus ambiguous in the elevation. Also, its visibility area is limited if the distance between the elements is more than $\lambda/2$. The effective array aperture depends on the DoD/DoA and the resolution capability is not uniform [40].

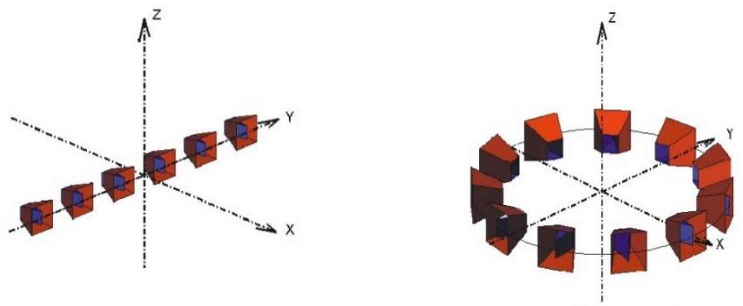


Figure 2 – left: a Uniform Linear Array (ULA) configuration, right: a Uniform Circular Array (UCA) configuration

2.1.2. Uniform Rectangular Array (URA)

This topology allows acquisition in both elevation and azimuth angles. In addition to azimuthal resolution, URA's also allow for elevation angle estimation. 2-D Unitary ESPRIT algorithms are well suited with this type of array due to its regular rectangular structure. Moreover, 2-D spatial smoothing can be carried out easily in order to cope with coherent waves (which is especially important in complicated micro- or picocell environments). A famous example of the application of this type of array is in the RUSK wideband vector channel sounder employed in [1].

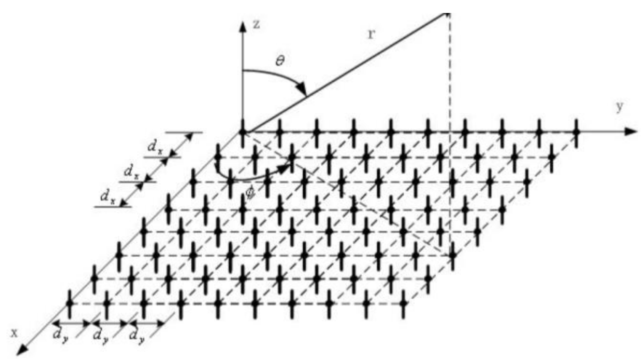


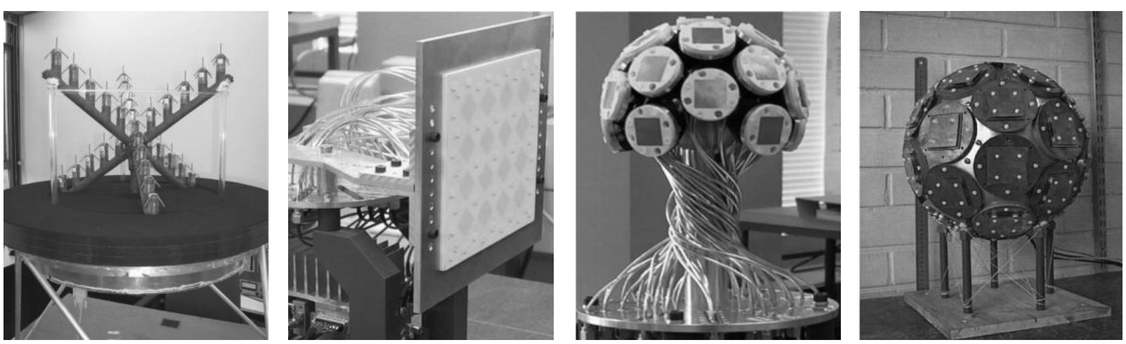
Figure 3 – A Uniform Rectangular Array (URA) configuration

2.1.3. Uniform Circular Array (UCA)

In this configuration, M identical elements are uniformly distributed around a circle. This structure can provide constant DOA estimation within the range of 0 ° to 360 ° and resolve two-dimensional angular sources of signal. This architecture's angular resolution capability is fairly uniform. However, though this system can be used to characterize the delay-angular properties of the channel with high resolution in azimuth (<5º), the resolution in elevation is poor (>5º) and there is ambiguity in the elevation domain.

2.1.4. Spherical and Semi-spherical Arrays

An optimal way for scanning the whole 4π angle in space would be to use an array mounted on a spherical surface. However, the geometry of the sphere does not allow uniform distribution of any number of elements on the sphere. Therefore, non-uniform inter-element distances and various relative polarization orientations of adjacent elements will complicate the design of spherical arrays. Moreover, optimization of the inter-element distance for circular and spherical arrays (or of the diameter in case of a fixed number of antenna elements) is required to minimize the side-lobes of the angular correlation function to reduce the probability of outliers in iterative parameters search. This typically leads to inter-element distances smaller than half a wavelength [41].
[27] resorts to using a semi-spherical array and therefore reducing the spatial angle capability of the spherical arrays from 4π to 360° in azimuth and 20° - 120° in elevation due to limitations in switching units. According to the article, the spherical geometry was chosen (among other options such as conical and cylindrical geometries) in order to contain more antenna elements than there were channels in the switch. This enabled the possibility to use different kinds of geometry setups and also the symmetrical structure would minimize the interference from adjacent elements [27].



(a) (b) (c) (d)

Figure 4 – Some of the popular array architectures used in literature, (a) Linear Crossed Array used in [24], (b) planar array, (c) hemispherical (semi-spherical) array used in [27], (d) spherical array used in [13], [29], and a number of other references.

2.2. Physical Vs. Virtual arrays

Virtual arrays, as opposed to 'real' or 'physical' arrays, are referred to array implementations using a single antenna which is moved or rotated to certain positions using matrix shifters or antenna rotators. The advantage of a virtual array configuration is mainly the fact that it lacks the interference and inter-element mutual coupling inherent in real architectures and that no calibration between the array elements is needed due to absence of neighboring elements. Moreover, the shape of the array can be arbitrary and flexible with respect to the application. It is also less expensive and easily reconfigurable from a hardware point of view. However, using arrays has the disadvantage of the slow measurement procedure: considering all the TX-RX positions, all the frequency samples taken, and all required temporal samples, positioning the element via a step motor might take longer periods than desired. Moreover, phase continuity in virtual arrays is a major concern when defining the direction of arrival [19].

2.3. Choice of Antenna Array Architectures

Antenna element design is mainly determined by requirements for bandwidth, uniform beam patterns, low inter-element coupling and polarization resolution. On the other hand, array design mainly determines the super-resolution algorithm which can be applied, the resulting accuracy and resolution as well as the resolvable spatial dimensions in terms of azimuth and elevation angles. Regular planar array structures (i.e. uniform linear arrays or uniform rectangular arrays (URA) can be used for 1-D (azimuth) and 2-D (azimuth/elevation) resolution, respectively. These require antenna elements with some directionally selective characteristic in order to remove the inherent front/back ambiguity of planar arrays. Moreover, a non-linear transformation from azimuth/elevation to the row/column element phase response is involved. This restricts the resolvable range to a sector of less than 180° (typically 120°).

In contrast, with circular antenna arrays the complete azimuth range of 360° can be covered. Realizations are given by the uniform circular array (UCA), the uniform circular patch array (UCPA) and the circular uniform beam array (CUBA). If elevation is of interest, vertically stacked UCPA or even spherical patch arrays (SPA) are possible solutions.

Double directional estimation requires arrays at both sides of the link and MIMO operation of the sounder. For cellular system consideration, a combination of planar and circular arrays is adequate, whereas for ad-hoc peer-to-peer networks identical circular arrays are most preferable [40].

Additionally, high and reliable resolution in terms of separation capability of closely spaced paths and low probability of outliers requires an antenna architecture which offers a minimum antenna array aperture size in the respective spatial dimension, including a minimum number of antenna elements, low antenna element coupling, and precise calibration. This has also to include the antenna switches and feeder cables.

3. Double-Directional Channel Sounding using Virtual Arrays: Representative Implementations

As previously mentioned, double-directional channel sounding aims at joint estimation of the wave vectors along with their polarizations in both ends of the transmitter-receiver link to arrive at a MIMO channel model which is independent of the transmit and receive antenna architectures and is solely dependent on the nature of the spatial channel. In order to implement a double-directional radio channel sounder, one approach is to rotate a dual-polarized directive antenna, which is dependent upon the assumption of a ‘frozen’ environment and also may not be efficient in terms of the 3-D rotation speeds at both ends of the radio channel. An alternative would be the use of virtual dual-polarized antenna arrays, which can be applied to the case of RSL’s Siradel project. We will introduce three different representative implementations of this approach in this chapter.

In [1] and [14] , wideband double directional channel sounding was carried out using a 16-element two-axis crossed virtual array at the TX side and a switched 8-element uniform linear array (±60° element beam width) at the RX side. The two-axis crossed array was chosen to allow high-resolution angle estimation over 360" azimuth, even though it also allows some elevation angle estimation as well. Without elevation capability, one could use a uniform circular array at the TX instead. A technique that alternatively uses estimation and beamforming, and is based on ESPRIT, is then performed on the data. As a result of this high resolution technique, it is reported that up to 50 distinct propagation paths were distinguished in a microcellular scenario.

In [10], a wideband 60 GHz three-dimensional channel sounder has been implemented using cubic virtual arrays at both TX and RX sides. The cubic shape was chosen to allow for direct capacity measurements from the data. The arrays are made of four elements per side with half the wavelength spacing between elements. For each array, an omnidirectional biconical antenna with 5 dBi gain in the azimuth plane and a half power beam width of 11° in elevation was used. The virtual arrays and the VNA are controlled linearly using a LabView-based interface; with the triggering of the VNA being based on the position of the antennas on the linear stages. It has been reported that Most of the measurement time (about 17 minutes) is used to move the linear stages to form the virtual arrays.

In [15], a MIMO radio channel sounder using virtual antenna arrays has been developed for Millimeter Wave measurements. The virtual arrays are either empty squares with five elements along each edge (a total of 16 elements – chosen as a compromise between accuracy in the angular domain and the duration of the measurements), or full squares with 5 × 5 elements (chosen in order to have a larger number of channels, which is required to calculate the channel capacities). Measurements in the LOS and the LOS obstructed scenarios with a 16-element array at both the TX and the RX are reported, as well as measurements in NLOS using a 25-element array at both the transmitter and receiver. The MIMO channel capacity is calculated for various numbers of elements per array: [2 · 2], [3 · 3], [4 · 4], and [5 · 5]. It is seen that the capacity increases almost linearly as a function of the number of elements, as stated in theory.

4. Conclusion And Recommendations

Current widespread interest in smart antennas as promises for higher capacity and better quality of service in the next generation wireless systems has led to investigations in different techniques for parameterization and characterization of the spatial radio channel. Towards this end, different novel antenna architectures and high resolution space-time signal processing algorithms have since been used in measurement-based channel sounding techniques. This survey presented a brief summary of the current state of the art in these areas.

One area which is open for further investigations is the tracking of radio channel parameters, or more precisely, the estimation of deterministic changes of channel parameters. The variations of the structural path parameters are closely related to the movement of objects influencing the radio channel. A first promising attempt has been made to estimate the parameter changes of the propagation path parameters using a linear model, but this area has generally been left out in characterization of channel parameters.

A further prospective research topic can be the optimal antenna array structure for channel sounding applications. Closely related to this issue is the calibration of antenna arrays, e.g., the estimation of the antenna array model especially the EADF. Since the upcoming channel sounding systems will have a larger bandwidth, the frequency dependence of the array response, e.g., the EADF is another interesting field which must be investigated in future works.

Finally, it is worth adding here that a virtual array sliding correlator implementation, along with ESPRIT as the signal processing algorithm, is recommended to RSL for use in their channel sounder for the Siradel project. The sliding correlator offers the distinct advantage of bandwidth compression through temporal dilation, making it an ideal approach for measuring the huge bandwidths of the ultra-wideband channel. This implementation also has the advantages of low cost, low losses, higher gain antennas, ease of reconfiguration, and robustness due to the use of Direct Sequence Spread Spectrum signals. DSSS also provides improved measurement dynamic range and low peak power levels, which allow the channel sounder to perform noninvasive measurements at interference-sensitive channels.

It is imposed by the Nyquist criterion that the element separation in antenna arrays be less than or equal to half a wavelength, which is about 8 cm. Therefore, an inter-element separation of 2-8 cm would be wise for the Siradel project's implementation. As for the number of elements in the array, there is a trade-off between the overall resolution and the measurement time, since with increases in the number of elements used in the arrays, the resolution of the corresponding system will increase, but this will further lead to more complicated post processing algorithms. The table below summarizes the relations among the element separation, the number of elements, and an estimate of the time required for the post processing algorithm.

Separation between the elements (cm)	**Number of Elements**	**Approximate Required time for Each Location of the Virtual Array**	**Approximate Required time for Each Location of the Virtual Array (after upgrading GPS up to 4 Pulses Per Second)**
2	25×25=625	625 points×4 polarizations×1 second = 41 min	10 min
4 (the preferred option)	12×12=144	10 min	2.5 min
6	8×8=64	4.5 min	1.5 min
8	6×6=36	2.5 min	less than 1 min

The motivation for applying the ESPRIT method in the channel sounder on the other hand, is its simplicity, efficiency, and the fact that it is less sensitive to noise and calibration errors than MUSIC and Root-MUSIC algorithms, as discussed in Section 1.3.

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