Measurement Site and Procedures for Experimental 2D DOA Estimation

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Abstract – **In this paper, a measurement site and experimental results of Two-Dimensional Direction of Arrival (2D DOA) estimation using 2D MUSIC algorithm are presented. Measurements are carried out in an anechoic chamber employing a horn antenna at the transmitting site and a rectangular 4 × 4 microstrip patch antenna array at the receiver. Measurement process is briefly described as well as the equipment and software used for that purpose. 2D MUSIC spectrum for different angular positions of source in azimuth and elevation is presented. Frequency dependency of DOA estimates is analysed.**

Keywords – **2D MUSIC, DOA estimation, frequency channel sounding, URA.**

I. INTRODUCTION

Direction of Arrival (DOA) estimation is well studied problem in recent years as it has numerous applications in wireless communication systems, military, acoustics, seismic, and medicine. Phase differences between signals collected by the array elements make it possible to calculate DOAs, and phase differences between the consecutive frequencies of the complex envelope at each element allow estimating the delays [1]. Using DOA estimation algorithms, both quality of received signals and capacity of mobile communication systems can be significantly improved. Further, there are a number of location-estimation techniques that are also based on DOA estimation. Employing two or more base stations, and adaptive arrays equipped with DOA estimation algorithms, they are able to determine the transmitter location by calculating the intersection of estimated DOAs from different base stations.

The most common algorithm for DOA estimation is MUSIC (MUltiple SIgnal Classification) [2]. This algorithm is well-known of its super-resolution capability as it provides highly-accurate DOA estimates. To do that, MUSIC needs "a priori knowledge" of signal characteristics as well as the total number of sources whose DOAs have to be estimated. Being a subspace-based algorithm, it performs eigen-decomposition of spatial covariance matrix that is formed from the received signals at different elements of an antenna array. In this paper, a system and procedures to provide these data experimentally are described as well as the results of 2D MUSIC algorithm. Since both azimuth and elevation angular positions are estimated, planar antenna array configuration is utilized due to its ability to scan three-dimensional (3D) space.

To provide hardware simplifications of a data acquisition system and to avoid requirements for a large number of receivers (one for each array element), frequency-domain channel sounding technique is employed. Measurements are based on the VNA (Vector Network Analyzer) that provides frequency response of the radio channel established between a transmitting and a receiving antenna [3]-[5]. There is only one receiver that is shared in time by use of RF switch matrix. In this way, signals to form a spatial covariance matrix are provided, and the matrix is further processed by 2D MUSIC algorithm. Measurements are done for three positions of the transmitting antenna in elevation, for a number of azimuth angles and frequency points. In our future research work, measurement data verified by MUSIC algorithm here will be used to further increase an efficiency of neural network models developed for fast and accurate DOA estimation [6].

The paper is organized as follows: Data model for 2D MUSIC algorithm is presented in Section II. System setup for measurements as well as the antennas and calibration procedure performed in the anechoic chamber are described in Section III. Measurement scenario and analysis of measurement results are given in Section IV. Section V contains conclusions remarks.

II. 2D MUSIC ALGORITHM

In this section, a description of the conventional approach to provide DOA estimates using the 2D MUSIC algorithm is given.

Let us suppose that signals of K sources illuminate a uniform rectangular array (URA) composed of $M \times N$ elements. Position of each element in the array can be denoted by its coordinates (m, n), where $m = 0, 1, 2, ..., M - 1$, and $n = 0, 1, 2, ..., N - 1$. Array element in the origin of the spherical coordinate system is taken as the reference one. Phase differences of signals received at all other array elements are defined relative to the reference. Further, it is supposed that the URA is placed in yz-plane, with distance between adjacent elements in y- and z-direction of dy and dz, respectively. Received signals at array elements can be written as

$$\mathbf{x} = \begin{bmatrix} \alpha_1 & \alpha_2 & \cdots & \alpha_K \\ \alpha_1 e^{j\Phi^{(1)}_{(1,0)}} & \alpha_2 e^{j\Phi^{(2)}_{(1,0)}} & \cdots & \alpha_K e^{j\Phi^{(K)}_{(1,0)}} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_1 e^{j\Phi^{(1)}_{(M-1,N-1)}} & \alpha_2 e^{j\Phi^{(2)}_{(M-1,N-1)}} & \cdots & \alpha_K e^{j\Phi^{(K)}_{(M-1,N-1)}} \end{bmatrix} \tag{1}$$

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where α_1, α_2, …, α_K are the amplitudes, and $\Phi^{(k)}_{(m,n)}$ represents the phase difference of the signal belonging to the k-th source, and received at array element with coordinates (m, n). $\Phi^{(k)}_{(m,n)}$ can be explicitly defined as follows

$$\Phi_{m,n}{}^{(k)}(\varphi_k,\theta_k)=\frac{2\pi}{\lambda}(d_y m\cos\theta_k\sin\varphi_k+d_z n\sin\theta_k) \qquad (2)$$

where k=1, 2, ... , K, φ_k and θ_k are DOAs of the k-th source, and λ is the wavelength of incident signals. Spatial covariance matrix can be estimated using the following formula

$$\mathbf{R}=\mathbf{x}\mathbf{x}^H \qquad (3)$$

If eigenvalues of matrix **R** are denoted by μ_i (i=1, 2, …, M*N), and keeping in mind that there are K incident signals, we obtain

$$\begin{gathered}\mu_1>\mu_2>\mu_3>\ldots>\mu_K>\sigma^2\\ \mu_{K+1}=\mu_{K+2}=\mu_{K+3}=\ldots=\mu_{M*N}=\sigma^2\end{gathered} \qquad (4)$$

where σ^2 stands for the thermal noise. On the basis of Eq. (4), it can be concluded that there are total K eigenvalues larger than the thermal noise. To determine the angular positions of K sources, a particular property of the sub-spaces spanned by the eigenvectors related to the large and the small eigenvalues of the **R** matrix is exploited. The beam-steering vectors virtually pointing towards the sources are linear combinations of the eigenvectors related to the large eigenvalues. Hence they must be orthogonal to the noise sub-space spanned by the eigenvectors related to the small eigenvalues in the **R** matrix.

If we denote the eigenvector that corresponds to eigenvalue μ_i (i = 1, 2, ..., M*N) by $\mathbf{e}_i$ (i = 1, 2, ... , M*N), then steering vector **a**, steering matrix **A**, and 2D MUSIC spectrum, P_{MU}, for angular positions φ and θ can be determined using the following expressions

$$\mathbf{a}_{m,n}{}^{(k)}(\varphi_k,\theta_k)=e^{j\Phi_{m,n}{}^{(k)}(\varphi_k,\theta_k)} \qquad (5)$$

$$\mathbf{A}(\varphi,\theta)=[\mathbf{a}^{(1)}_{(m,n)}(\varphi_1,\theta_1)\ \ \mathbf{a}^{(2)}_{(m,n)}(\varphi_2,\theta_2)\ \ \ldots\ \ \mathbf{a}^{(K)}_{(m,n)}(\varphi_K,\theta_K)] \qquad (6)$$

$$\begin{aligned}P_{MU}&=\frac{1}{\sum\limits_{i=K+1}^{M*N}\left|\mathbf{e}_i^H\mathbf{A}(\varphi,\theta)\right|^2}\times\mathbf{A}^H(\varphi,\theta)\mathbf{A}(\varphi,\theta)\\ &=\frac{\mathbf{A}^H(\varphi,\theta)\mathbf{A}(\varphi,\theta)}{\mathbf{A}^H(\varphi,\theta)E_N E_N^H\mathbf{A}(\varphi,\theta)}\end{aligned} \qquad (7)$$

where

$$E_N=[e_{K+1}\ \ e_{K+2}\ \ .\ .\ .\ e_{M*N}] \qquad (8)$$

In other words, 2D MUSIC algorithm performs spectrum search for all angles in azimuth and elevation. In case the orthogonality condition is fulfilled, the Eq. (7) will give a strong peak since the denominator approaches zero.

III. SYSTEM SETUP

Vector network analysis of a signal is a method to accurately characterize its components by measuring their effect on amplitude and phase of the swept-frequency. Therefore, short distance measurement of radio channel characteristics, based on the use of VNA, represents very attractive measurement technique because of very simple implementation requirements, relative flexible system, and ability to track system error [1]. By the use of frequency sweep technique wide dynamic range can be provided for measurements. Further, it is possible to directly measure absolute losses due the path loss between two observed antennas. On the other side, disadvantage of this measurement method is slow measurement time and requirements for long cables to transmit the referent signal what limits its use on short-distance links with relatively stationary channel.

The measurement system shown in Fig. 1 is based on VNA (HP 8510) and frequency converter (HP 8511A). Frequency-channel sounding is carried out by sweeping a set of narrowband sinusoid signals through a frequency band. The VNA operates in the transfer function mode where one of its ports serves as the transmitting port and the other as the receiving port. Scattering S_{21} - parameter is used to express the complex frequency channel transfer function. VNA sends a frequency tone f through the channel and channel transfer function is represented as $S_{21}(f)$.

At the receiving site, each array element is through the coax cable connected to the appropriate input of RF switch matrix (Fig.1). The signal from the matrix is then guided to the second port of the VNA. Array elements are switched sequentially, where only one array element is active in a moment while other elements are present as dummy elements. Measurements at the network analyzer are averaged 16 times. At each angular position in the anechoic chamber 15 snapshots are recorded.

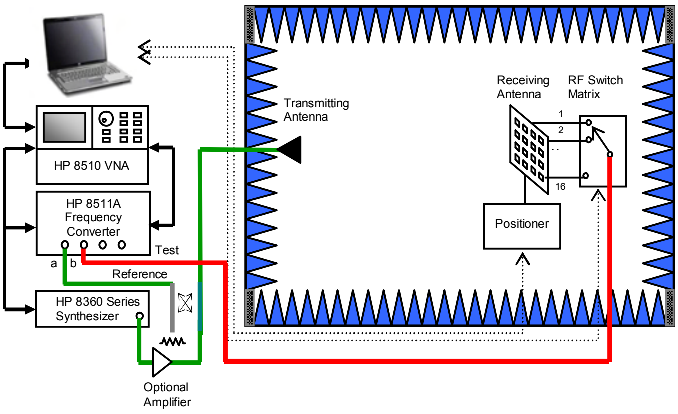
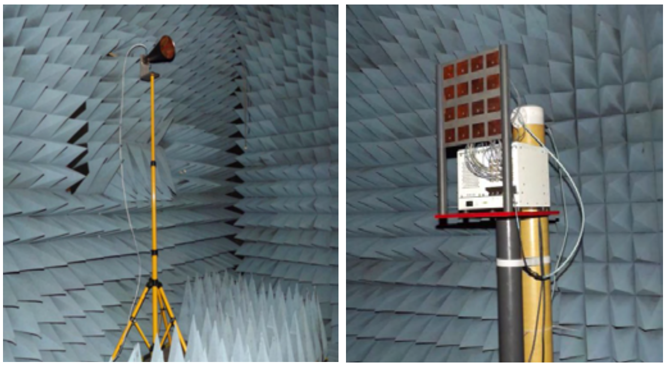


Fig. 1. Block scheme of the measurement system

To run the measurement routine automatically, VNA and the positioner in the anechoic chamber are controlled by the MATLAB software. Existing software for standard antenna measurements, SPAM 3D, is upgraded to implement RF switch matrix as a new instrument in the measurement setup. Code for the matrix control (selecting one of the 16 channels) is written in C, DLLs (Dynamic Link Libraries) are created and called from MATLAB. Previously, channels of RF switch matrix are properly configured and tested using MAX (Measurement & Automation Explorer). Positioner in the anechoic chamber is able to rotate in azimuth only, in the smallest step of 1°. To make measurements for different elevation positions it is necessary to change the height of the transmitting antenna.

A. Antennas

As a transmitting antenna, a double-polarized quad-ridged horn antenna (model no. A6100), operating in the frequency band 2.18 - 20 GHz, is employed (Fig. 2 (a)). The gain of the antenna is around 7 dBi at 2.44 GHz. At the receiving site, a rectangular antenna array is positioned, composed of 16 (4 x 4) microstrip patch antennas with resonant frequency at 2.44 GHz (Fig. 2 (b)). Dimensions of microstrip patches are optimized in CST Microwave Studio, (*L*=39.6 mm, *W*= 49.4 mm) and realized on Rogers RT5880 Duroid substrate (epsilon=2.2, thickness=1.57 mm). Measured return loss of a single patch is -37 dB, and measured gain is 6.7 dBi at resonant frequency.



(a) (b)

Fig. 2. Transmitting antenna mounted on the tripod (a), receiving array with RF switch matrix behind placed on the antenna tower (b)

B. Calibration of a system

Calibration procedure is necessary to remove errors caused by the source, and more important, to eliminate all frequency dependent effects of a measurement system such as reflections in cables and connectors. The accuracy of the calibration procedure efficiently sets the dynamic range of the measurement system. To measure a transmission, as it is case with the characterization of a radio channel, response calibration is needed. Calibration results are then used to correct system errors of frequency response [1], [3].

Transfer function S_{21} of the complete system is measured in the anechoic chamber using reference antennas on mutual distance of 5.1 m and height of 1.90 m. Calibration data are recorded for each channel of RF switch matrix separately, and used later in the post-processing to normalize measured data. It is known that any change between the calibration and test setups can cause errors in measurement results such as multiple reflections on transmitting and receiving site due to the impedance change (when antenna elements are switched) and changes of cable characteristics due to flexures. To minimize such errors it is very important not to move any instrument or cable while the measurement is running.

IV. MEASUREMENT SCENARIO AND RESULTS

Measurements are performed as follows:

1) Transmitting antenna is set on a certain height on a tripod.
2) Receiving antenna array is rotated to a position in azimuth.
3) A channel of the RF switch matrix is selected and frequency sweep in the band from 2.41 to 2.47 GHz (51 pts) is performed. This procedure is repeated for all 16 channels.
4) Antenna tower is rotated to other position in azimuth, and array elements are switched. This is done for all required azimuth positions.
5) Results are saved in a .mat file.
6) Height of the transmitting antenna is increased by 10 cm (2.00 m) and set of data is recorded.
7) Height of the transmitting antenna is decreased by 50 cm (1.40 m) and set of data is recorded.

2D MUSIC spectrums, for three angular positions of the transmitting antenna, are plotted in Figs. 3, 4 and 5. Reference DOAs are (6°, 1.15°), (-30°, 0°) and (27°, -5.6°), and corresponding estimates are (9.11°, 1.12°), (-29.83°, 1.37°) and (31.83°, -4.11°). Figs. 6 and 7 present these values separately for azimuthal and elevation plane. Solid lines are plotted for DOA estimates and vertical dotted lines present the expected angular positions. It can be concluded that measured values are in good agreement with reference DOAs. For θ = 0°, estimation of azimuth angle is the most accurate. On the other side, there is an error of 1.37° for the elevation angle that could appear due to mutual coupling between antenna elements or non perfect alignment of the transmitting and receiving antenna during the measurement. The largest error is 4.83° for the azimuh angle, made for the elevation angle θ = -5.6°.

In Fig. 8, DOA estimates are plotted as a function of azimuth angles from -45° to 45°, and frequencies from 2.41 GHz to 2.47 GHz. As frequency shift corresponds to very small change of the wavelength of the incident signal (approximately $\lambda/50$), it can be observed that performances of URA for DOA estimation are not significantly deteriorated for lower and upper frequencies of its impedance bandwidth.

V. CONCLUSION

In this paper, measurement site for 2D DOA estimation is described, and performances of 2D MUSIC algorithm are evaluated. All measurements are carried out in an anechoic chamber taking into the consideration only the direct signal between the transmitting and the receiving antenna. As it is demonstrated, a 16-element microstrip patch array has good performance for 2D DOA estimation. To provide more accurate 2D DOA estimates, mutual coupling between array elements should be compensated performing careful calibration procedure for the array.

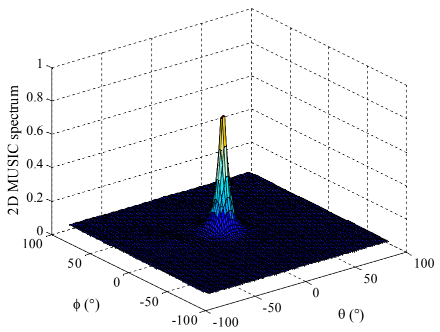


Fig. 3. 2D MUSIC spectrum for source position (φ, θ)= (6°, 1.15°)

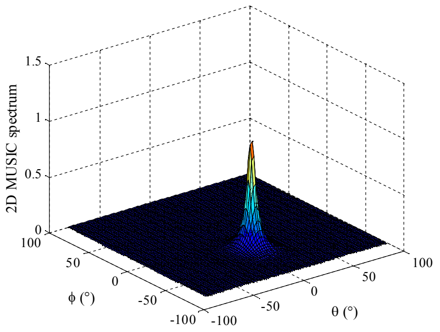


Fig. 4. 2D MUSIC spectrum for source position (φ, θ)= (-30°, 0°)

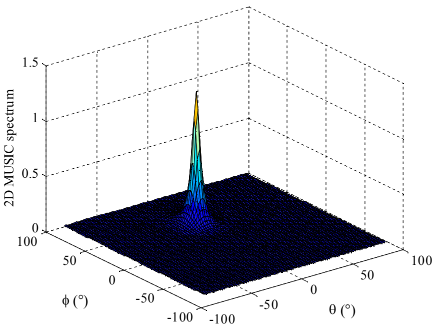


Fig. 5. 2D MUSIC spectrum for source position (φ, θ)= (27°, -5.6°)

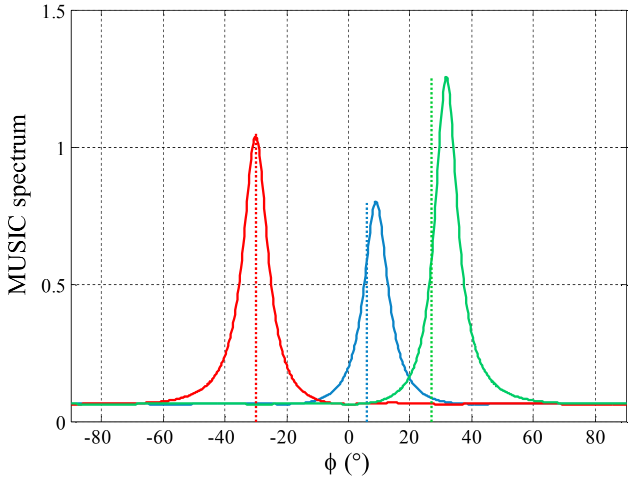


Fig. 6. Angular positions in azimuth (solid lines - DOA estimates, dotted vertical lines – actual positions)

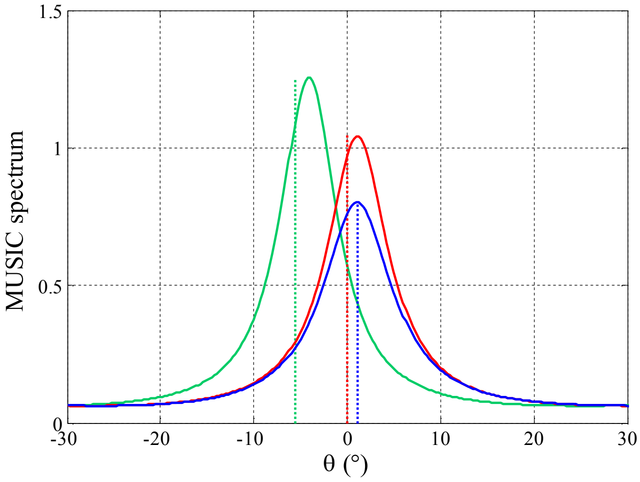


Fig. 7. Angular positions in elevation (solid lines - DOA estimates, dotted vertical lines – actual positions)

ACKNOWLEDGEMENT

This paper is a joint work of the project TR-32052 of the Serbian Ministry of Education and Science and the project CARE (Coordinating the Antenna Research in Europe). Measurements are performed at the Institut für Hochfrequenztechnik und Elektronik, Karlsruhe Institute of Technology, Karlsruhe, Germany.

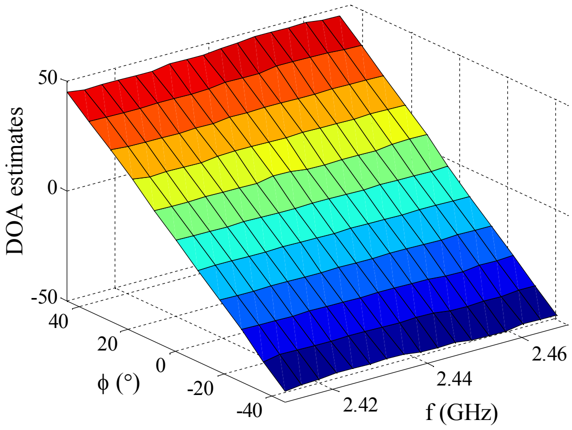


Fig. 8. Frequency dependency of DOA estimates for azimuth positions φ = [-45°, 45°] and elevation θ = 0°

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