UNIFORM RECTANGULAR SMART ANTENNA – MICROSTRIP ELEMENT MODELING AND SIGNAL DIRECTION ESTIMATION

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Abstract

This paper focuses on the smart antenna design steps – antenna element and uniform rectangular array modeling, an estimation of the direction of arrival (DOA) and adaptive antenna pattern creation.

For the rectangular patch antenna design is used the transmission line model (TLM). For the design procedure is specified the substrate (its relative dielectric constant and height) and the operating frequency. Numerical results derived by Matlab for patch element radiation pattern are shown.

The DOA estimation method is introduced for the significant improvement in smart antenna resolution. The DOA estimation involves a correlation analysis followed by signal/noise subspace formation and eigenstructure analysis. The 2-D unitary ESPRIT is presented for direction of arrival estimation analysis of the array. Limited numerical examples on the base of Matlab simulations are depicted to illustrate this algorithm.

1. INTRODUCTION

The smart antenna with microstrip (patch) elements is probably the most suitable class antennas for wireless communications. An appropriate adaptive array structure is a rectangular smart antenna with uniformly distributed patch elements because it owns the ability to scan the main beam in any direction of azimuth and elevation in 3-D space [1].

In antenna array modeling, the microstrip antennas are the most widely used class elements on account of their low cost, low profile. These antennas are simple to manufacture, mechanically robust, with a variety of impedance, polarization, and pattern characteristics [2].

In this paper, the direction of arrival (DOA) method is applied to antenna array modeling. The model descriptions are attended by simulation results obtained for a specific uniform rectangular array (URA).

2. THE SMART ANTENNA MODELING

2.1. The Microstrip Element Analysis and Calculation

The rectangular patch element is the most suitable and very easy for mathematical analysis. The microstrip antenna geometry is illustrated in Fig. 1, where the patch with length *L* ($0.33\lambda_0 \le L \le 0.5\lambda_0$, λ_0 is the wavelength in the free space), consist of a very thin metallic patch with a thickness *t* ($t << \lambda_0$) placed on a dielectric substrate with a thickness *h* ($0.003\lambda_0 \le h \le 0.05\lambda_0$) above a perfectly conducting ground plane [3].

For the analysis and design of the rectangular microstrip element is applied the transmission line model (TLM) which gives accurate enough results with simple calculations. For the antenna modeling, the patch is described as a configuration of two radiating slots with width *W*, height *h*, separated by a transmission line with length *L* into a dielectric with an effective dielectric constant ε_{reff} and here is assumed that only the principal mode TM^{x}_{010} propagates in this line.

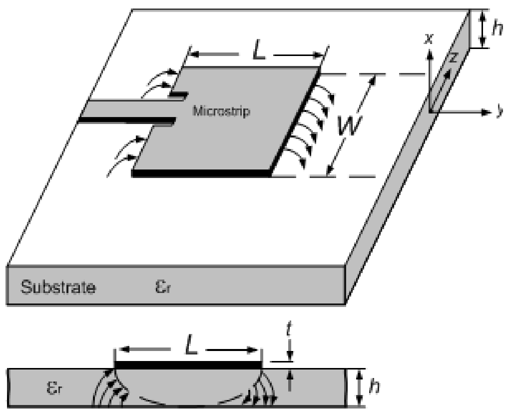

Fig. 1. The rectangular patch element geometry

For the design procedure is necessary to specify the substrate parameters (ε_r-relative dielectric constant, *h*-height) and the resonant (operating) frequency f_r. The procedure steps are:

- width calculation:

$$W = \frac{1}{2 f_r \sqrt{\mu_0 \varepsilon_0}} \sqrt{\frac{2}{\varepsilon_r + 1}} \quad (1)$$

- effective dielectric constant:

$$\varepsilon_{r\,eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 12\, h / W}} \quad (2)$$

- length extension ΔL and effective patch length computations (Figure 2):

$$\Delta L = 0.412\, h \frac{(\varepsilon_{r\,eff} + 0.3)(W/h + 0.264)}{(\varepsilon_{r\,eff} - 0.258)(W/h + 0.8)} \quad (3)$$

$$L = 1 \Big/ 2 f_r \sqrt{\mu_0 \varepsilon_0 \varepsilon_{reff}}, \qquad L_{eff} = L + 2\Delta L \quad (4)$$

The input impedance is determined using the following formulas [4]:

$$R_{in} = \frac{1}{2(G_1 + G_{12})}, \quad R_{in}(y = y_0) = R_{in} \cos^2\left(\frac{\pi}{L} y_0\right) \quad (5)$$

$$G_1 = \frac{-2 + \cos(k_0 W) + (k_0 W) S_i(k_0 W) + \frac{\sin(k_0 W)}{k_0 W}}{120\pi^2} \quad (6)$$

where G_1 is the conductance of a single radiating slot, k_0 is the free space phase constant, $S_i(X)$ is a sine integral, G_{12} is the mutual conductance between the two radiating slots (often neglected in first approximation).

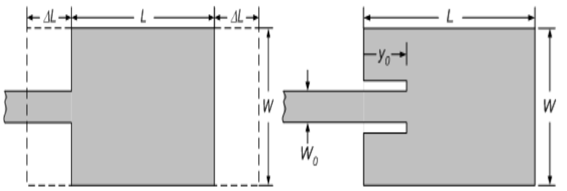

Fig. 2. The microstrip antenna parameters

For the modeling procedure is necessary to calculate the microstrip element directivity [3]

$$D_{patch} = D_0 \frac{2G_1}{G_1 + G_{12}} \quad (7)$$

$$D_0 = \frac{2\pi W / \lambda_0}{-2 + \cos(k_0 W) + (k_0 W) S_i(k_0 W) + \frac{\sin(k_0 W)}{k_0 W}} \quad (8)$$

where D_0 is the directivity of a single slot. In the first approximation after neglecting G_{12} the patch antenna directivity is $D_{patch} \approx 2D_0$.

2.2. The URA Smart Antenna Structure

The URA array with N x M (M, N – even) equally distributed identical patch elements is located symmetrical in *x-y* plane (in Figure 3 their center positions are shown by dots). The origin of coordinate system is located at the center of the array. An incoming narrowband signal arrives at the array from elevation angle θ and azimuth angle ϕ.

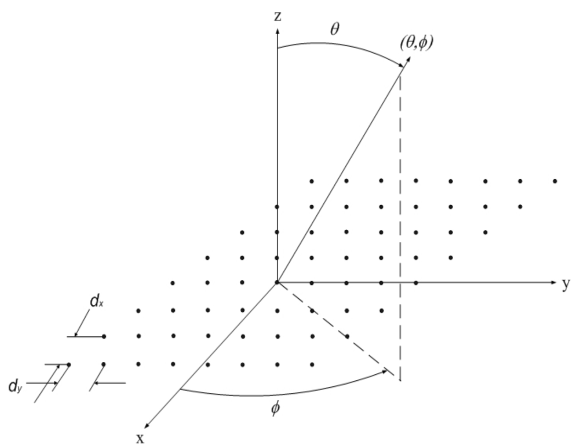

Fig. 3. URA geometry, along with an incoming signal

The *array factor (AF)* of URA with its maximum along (θ_0, ϕ_0) can be calculated using the following expression [3]

$$[\mathrm{AF}(\theta, \varphi)]_{\mathrm{MxN}} = \\ = 4 \sum_{m=1}^{M/2} \sum_{n=1}^{N/2} \mathrm{A}_{mn} \cos[(2m-1)u] \cos[(2n-1)v] \quad (9)$$

where

$$u = \frac{\pi d_x}{\lambda} (\sin\theta \cos\phi - \sin\theta_0 \cos\phi_0) \quad (10)$$

$$v = \frac{\pi d_y}{\lambda}\left(\sin\theta\sin\phi - \sin\theta_0\sin\phi_0\right) \qquad (11)$$

where A_{mn} is the amplitude excitation of the individual element, and (d_x, d_y) are the inter-element spacing along the x-axis and the y-axis, respectively.

2.3. 2-D Unitary ESPRIT

The DOA algorithm determines the directions of incoming on the URA signals based on the time delays. These delays depend on array geometry, number of elements, and inter-element spacing. The DOA estimation involves a correlation analysis followed by signal/noise subspace formation and eigenstructure analysis.

For the URA of Figure 3, the time delay of the narrowband signal at the (*m*, *n*)th element with respect to the origin, is written as [4]

$$\tau_{mn} = \frac{m d_x \sin\theta\cos\phi + n d_y \sin\theta\sin\phi}{c} \qquad (12)$$

where *c* is speed of light in free space.

For the significant improvement in smart antenna resolution 2-D Unitary ESPRIT (*Estimation of Signal Parameters via Rotational Invariance Technique*) method is applied. This algorithm is a technique for accurate direction of arrival signal computation in the real time on the base of array matrix analysis. Applying this method under the conditions of a URA structure (Figure 3), the five basic steps of real valued estimation are briefly described [5]:

1. Compute E_s via *d* "largest" left singular vectors of [Re{Y}, Im{Y}] where $\mathbf{Y} = \left(\mathbf{Q}_M^H \otimes \mathbf{Q}_N^H\right)\mathbf{X}$.

2. Calculate $\boldsymbol{\psi}_\mu$ as the solution to the [*(N-1)M x d*] $\mathbf{K}_{\mu 1}\mathbf{E}_s\boldsymbol{\psi}_\mu = \mathbf{K}_{\mu 2}\mathbf{E}_s$ matrix equation.

3. Compute $\boldsymbol{\psi}_\nu$ as the solution to the [*(N-1)M x d*] $\mathbf{K}_{\nu 1}\mathbf{E}_s\boldsymbol{\psi}_\nu = \mathbf{K}_{\nu 2}\mathbf{E}_s$ matrix equation.

4. Compute λ_i, *i=1,…,d*, as the eigenvalues of the (*d x d*) matrix $\boldsymbol{\psi}_\mu + j\boldsymbol{\psi}_\nu$.

5. Compute spatial frequency estimates $\mu_i = 2\tan^{-1}\left(\mathrm{Re}\{\lambda_i\}\right)$ and $\nu_i = 2\tan^{-1}\left(\mathrm{Im}\{\lambda_i\}\right)$, *i=1,…,d*.

3. SIMULATION RESULTS

Simulation results and numericall examples are based on the theory depicted above. The design procedure was realized on the base mathematical calculations and Matlab simulations presented in Table 1 and Figure 4 [6]. The modeling smart antenna element was rectangular microstrip antenna operating at frequency 2.4 GHz and using substrate with parameters $\varepsilon_r = 2.2$ and $h = 0.1588$.

The DOA estimation is investigated under the conditions of a URA structure with modeling rectangular patch elements described above. The method described in Section 2 is utilized to perform the estimation [4].

Table 1. Modeling results for patch element

Patch parameters	Mathematical calculation	Matlab simulation results
Physical width [cm]	4.9411	4.9411
Physical length [cm]	4.1373	4.1356
Effective length [cm]	4.3047	4.3030
Resonant input resistance [omhs]	244.5795	244.7745
Feed point position [cm]	1.4504	1.4504
Directivity [-]	5.0295	5.2118
Directivity [dB]	7.0152	7.1699

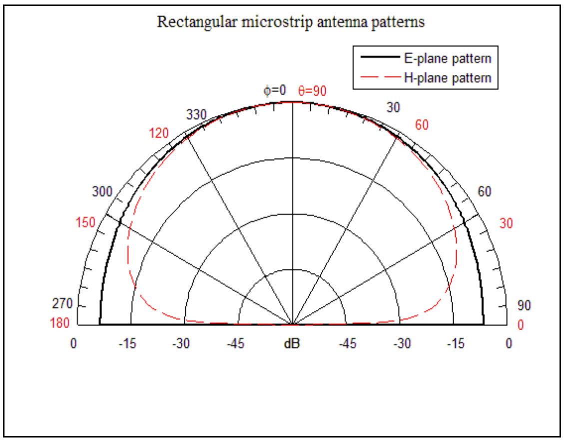

Fig. 4.The rectangular microstrip element radiation pattern

To illustrate the DOA algorithm applicability for URA, is considered the case where the URA with N=8 and M=8 elements and interelement spacing (the center-to-center separation between elements) $d_x = d_y = 0.45\lambda$ is examined. The *signal of interest* (SOI) incomes from ($\theta = 60^0, \phi = 100^0$), while the three *signals not of interest* (SNOI) are directed from ($\theta = 20^0, \phi = 70^0$), ($\theta = 40^0, \phi = 120^0$) and ($\theta = 90^0, \phi = 155^0$) are given in Table 2. Analyzed type of array is investigated in the presence of the *Additive White Gaussian Noise* (AWGN) with the zero mean, and variance 0.1. The results demonstrate its ability for accurate estimation, great performance, and *robustness*. Simulation results, utilizing the 2-D unitary ESPRIT algorithm give precise data when adapt the smart antenna pattern.

Table 2.The DOA data and estimation obtained utilizing 2-D unitary ESPRIT

URA structure	Data
Number of elements	M=8 ,N=8
Interelement spacing	0.45λ
Number of incoming signals	1
Number of data samples	2000
Actual direction data	
SOI	$\theta_1=60^0$, $\varphi_1=100^0$
SNOI 1	$\theta_2=20^0$, $\varphi_2=70^0$
SNOI 2	$\theta_3=40^0$, $\varphi_3=120^0$
SNOI 3	$\theta_1=90^0$, $\varphi_1=155^0$
DOA direction estimations	
SOI	$\theta_1=59.9998^0$, $\varphi_1=100.0977^0$
SNOI 1	$\theta_2=20.9928^0$, $\varphi_2=69.9951^0$
SNOI 2	$\theta_3=40.0031^0$, $\varphi_3=120.0897^0$
SNOI 3	$\theta_1=89.9995^0$, $\varphi_1=154.9997^0$

4. CONCLUSION

This paper investigates the issues for a single rectangular patch element design procedure and a uniform rectangular smart antenna structure modeling with microstrip elements.

Numerical simulation results are illustrated that the patch element design gives accurate results, and that the antenna geometry configuration with M=N=8 microstrip elements is an optimal scenario, because the DOA estimations are proved to be accurate and stable enough, and the smart antenna pattern creation is affected by the type of elements, size and geometry of the antenna array.

A brief theory of antenna array to distinguish the direction of arrival by 2-D ESPRIT algorithm is considered that is used as a DOA technique.

The rectangular adaptive array with uniformly distributed microstrip elements used here is analyzed based on the TLM method (for a single patch element representation) and the 2-D unitary ESPRIT technique (for the smart array calculation). The influence of different design parameters is explored assuming a monochromatic plane wave excitation coming from a specific direction. Then the specified iterative algorithm is applied to estimate the DOA.

This theory was supported by suitable numerical data (see the Table 2). The direction of arrival estimation for array pattern creation was examined. Matlab programs are used for simulations. The simulations show very good agreement between the assumptions and estimations.

5. ACKNOWLEDGMENT

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