Interference Immunity of Signal Processing in the Presence of Interferences in Information System by Means of Optimal Loading Matching

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Abstract. An information system with multi-channel receiving system and mutual influence of channels is considered. Signal and interference are spatially concentrated sources of radio emission. The mutual influence of channels is researched by calculating the matrix of mutual impedances for thin vibrators. The magnitude of the load impedances in individual channels influences the resulting signal-to-interference ratio. Also, the value of the load impedances depends on correlation properties of the signal and interference at the input of the spatial channels. It complicates the problem of optimal matching. The problem of finding the optimal load impedances as a function of the signal-interference ratio is solved. The solution of the optimization problem is carried out by a numerical analysis using the MatLab or, in a particular case, by the analytical method. The optimal load impedances are compared depending on the degree of mutual influence of the channels of the information system, spatial structure, and interference parameters. Comparing the optimum load impedances, spatial structure and parameters of interferences is carried out depending on a degree of mutual influence of the information system channels. The output signal-interference ratio behavior at different values of the load impedances is researched. The gain of optimal matching versus the load impedances is calculated in the absence of mutual influence and in the case of applying non-optimal mutual impedances when there is the mutual influence.

Keywords: Interference mutual influence, mutual impedances, information system, signal processing

1 Introduction

Evolution of the integral semiconductor technology, microwave solid state high efficiency amplifiers, and super high frequency digital circuitry stimulate design of radio systems with signal processing in spatial channels of antenna array (AA) [1 – 3]. Often, characteristics of the AA are obtained without mutual influence of the elements. It is obtained with multiplying the beam pattern of one element by the factor AA. If there is a significant mutual influence of the elements, the characteristics of a real antenna can differ from the calculated characteristics.

In paper [4], the effect of mutual coupling on the performance of adaptive antennas has been a topic of considerable interest. The mutual influence can lead to deterioration and improvement of antenna array characteristics. For adaptive antennas based on minimizing the mean squared error between the array output and a locally generated reference signal, the mutual coupling between antenna elements hardly affects the nulling performance of adaptive antennas. In fact, in a given size aperture, as the number of antenna elements is increased one obtains better nulling performance irrespective of the increased mutual coupling between antenna elements. Paper [5] deals with the near-field DOA-Matrix method for source localization using a uniform linear array antenna. The mutual coupling between array elements degrades the DOA estimation accuracy. Influence of the mutual coupling in source localization using the near-field DOA-Matrix method and the improved method is investigated. Paper [6] deals with direction-of-arrival estimation for very closely spaced dipoles. The mutual coupling can produce amplitude and phase difference of embedded element patterns, which can be utilized to greatly improving the direction-of-arrival estimation performance by incorporating the pattern diversity into the estimation algorithm. In paper [7], there is analysis of the noise immunity of signal processing in the antenna array with influence of the elements in the form of thin vibrators in presence of the spatially concentrated and spatially extended jammers. It is established that mutual influence can lead to both increase and a decrease in noise immunity. In paper [8], analysis of nonlinear properties of receiver channels for coherent and noncoherent composition of intermodulation interferences at output of each RF stage is performed. Spatial correlation matrices of the sum of active and intermodulation interferences for active antenna array are evaluated with and without mutual influence of the antenna elements. The results of recent studies prove the importance of mutual influence the basic characteristics of radio systems. The mutual influence of the antenna elements affects not only the directivity characteristics of the antenna array and the signal-to-noise ratio at its output, but, also, the output impedances of each of the AA elements [9, 10]. The value of the output impedances in the presence of mutual influence of the elements of the AA also depends on the amplitude-phase relations of the signals and the noise. The choice of load impedances is a difficult computational task. The object of this work is to investigate the influence of the mutual impedances of the antenna array to the noise immunity of signal processing in the presence of spatially concentrated noise. Matching the impedance load of the antenna elements is important for different signals, interference parameters, and the spatial structure of the AA.

2 Statement of problem

The antenna array includes N omnidirectional elements arranged in a certain way in space. In space, there are signal source of variance D_S and M interference of variance D_m, $m = 1, \ldots, M$. The spatial position of signal sources and interference is defined by the vectors $\boldsymbol{V}_S$ and $\boldsymbol{V}_m$, $m = 1, \ldots, M$ respectively. The spatial correlation matrices of the signal and interference in the elements of the antenna array are equal to $\boldsymbol{R}_S = D_S \boldsymbol{V}_S \boldsymbol{V}_S^{\mathrm{H}}$, $\boldsymbol{R}_J = \sum\limits_{m=1}^{M} D_m \boldsymbol{V}_m \boldsymbol{V}_m^{\mathrm{H}}$, where the sign H means Hermitian transpose.

The mutual influence of the antenna array elements affects to the characteristics of the signal and interference at output. The value of mutual influence is characterized by a matrix of mutual impedances $\boldsymbol{Z}$ [9,10]. The electric field strength in the vicinity of AA is related to the voltage at the load impedances of the AA elements by the relation $\boldsymbol{U} = \boldsymbol{Z}_L(\boldsymbol{Z} + \boldsymbol{Z}_L)^{-1}\boldsymbol{J}$ [7], where $\boldsymbol{Z}_L$ is the diagonal matrix with a vector of load impedances $\boldsymbol{V}_L$ on the main diagonal. As a result, the correlation interference matrices and the form of the output sugnal at the AA elements are: $\boldsymbol{R}_U = \boldsymbol{Z}_1 \boldsymbol{R}_J \boldsymbol{Z}_1^{\mathrm{H}}$, $\boldsymbol{S}_1 = \boldsymbol{Z}_1 \boldsymbol{S}$, where $\boldsymbol{Z}_1 = \boldsymbol{Z}_L(\boldsymbol{Z} + \boldsymbol{Z}_L)^{-1}$ means the coefficient of signal transmission from the inputs of the AA elements to their outputs.

In addititon to external interference, there are internal noise in the system caused by losses from the diagram-making circuit and frontend of receivers of the active antenna. The total noise power associated to AA elements load is equal to

$$P_n = kT\mathit{\Delta} f \left(\operatorname{Re}\left\{ \frac{R_{11}}{Z_L} \left| \frac{Z_L}{Z_L + Z_{11}} \right|^2 \right\} + NF - 1 \right),$$

where $k = 1,38 \times 10^{-23} J/K$ is the Boltzmann constant, T is the temperature (degrees Kelvin), $\mathit{\Delta} f$ is the bandwidth, R_{11} is the active component of the antenna element impedance equal to the emitting resistance, $\underline{Z}_L$ is the load impedance, NF is the frontend noise factor. Power of the signal in the load of the antenna element is: $P_S = \operatorname{Re}\left\{ \frac{|U|^2}{Z_L} \right\}$. As a result, the signal-to-noise ratio $q = P_S/P_n$ depends on the load impedance. Next, it should be taken into account the load impedance optimization. In the antenna array, we assume that the noises in the impedance load are not correlated to each other and have a diagonal correlation matrix $\boldsymbol{R}_T$ with signal power vector:

$$\boldsymbol{P}_T = \{P_n, n = 1, \ldots, N\}$$

on the main diagonal.

The correlation matrix of the interference, which emitted in the load impedance is equal to $\boldsymbol{R}_{IL} = \overline{\boldsymbol{U}_L \boldsymbol{U}_L^{\mathrm{H}}}$, where $\boldsymbol{U}_L = \boldsymbol{U} \times \sqrt{\operatorname{Re}\{1/\boldsymbol{V}_L\}} =$ $= \left\{ U_n \sqrt{G_n}, n = 1, \ldots, N \right\}$ is the normalized value of interference at the load impedance, $G_n, n = 1, \ldots, N$, is the active conductivity of the load. As a result, the correlation matrix of noise and noise at the output of AA elements with taking into account their mutual influence is equal to

$$\boldsymbol{R}_1 = \left(\boldsymbol{Z}_1 \boldsymbol{R}_J \boldsymbol{Z}_1^{\mathrm{H}} \right) \times \left(\sqrt{\operatorname{Re}\{1/\boldsymbol{V}_L\}} \left(\sqrt{\operatorname{Re}\{1/\boldsymbol{V}_L\}} \right)^T \right) + \boldsymbol{R}_T.$$

The signal at the load impedance is equal to $\boldsymbol{S}_L = (\boldsymbol{Z}_1 \boldsymbol{S}) \times \sqrt{\operatorname{Re}\{1/\boldsymbol{V}_L\}}$. The signal-to-interference ratio is obtained as a result of optimal processing the signal from the output of the elements AA. It is equal to [11] $q = \boldsymbol{S}_L^{\mathrm{H}} \boldsymbol{R}_1^{-1} \boldsymbol{S}_L$.

3 Interference immunity evaluation

There is calculating of the signal-to-noise ratio depending of the receiving system spatial structure with different modes of the load matching. Suppose that the elements of AA are equidistant and that the AA is spatially linear. The calculation is carried out for antenna elements in the form of thin vibrators, which are located vertically. The value of the mutual impedance between two any vibrators is equal to [9,11]

$$Z_1 = 30\Big\{2Ei(jk_0d) - 2Ei\Big[-jk_0(\sqrt{d^2+L^2}+L)\Big] \\ -2Ei\Big[-jk_0(\sqrt{d^2+L^2}-L)\Big]\Big\},$$

where $Ei(\pm jx) = Ci(x) \pm jSi(x)$ is the integral exponential function. It is calculated on the basis of the functions of the integral cosine and integral sine with $k = \frac{2\pi}{\lambda}$ as the wave number, d the distance between the vibrators, L the length of vibrator. With a large spatial separation of the vibrators AA, the mutual influence becomes insignificant and the matrix of mutual impedances is $\boldsymbol{Z} = \boldsymbol{I} \times (73.1 + j42.5)\Omega$.

Optimization of the load impedance is a difficult calculational problem. Commonly, it solved by numerical methods. The optimal load impedances also depend on the angular position of the signal and the interference sources.

Consider an example of an analytical solution of the problem of optimal matching for an antenna array with two elements ($N = 2$). The field of each antenna element is inphase. This ensures the symmetry of the problem. With a large distance between the elements, the mutual coupling is negligible. The output resistance of a thin vibrator is equal to $(73.1 + j42.5)\Omega$. Optimal value of each of the antenna elements loads impedance $Z_L = (73.1 + j42.5)\Omega$. An equivalent circuit that shows the effect of the mutual impedance of the AA elements is given in Fig. 1.

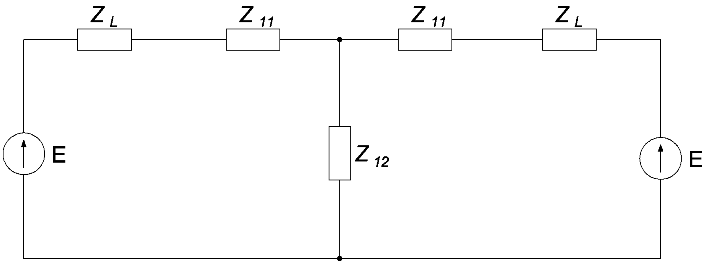
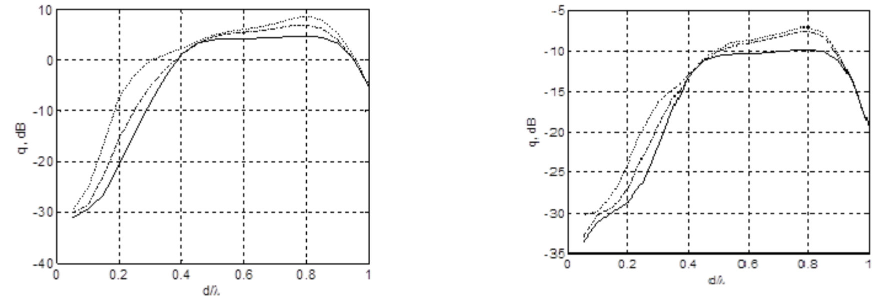


Fig. 1. Equivalent circuit of a 2-element inphase antenna array

In the example, the currents in the circuit of each antenna element are the same and equal $I = \frac{E}{Z_l + 2Z_{12}}$. The power in the load of one of the elements is $P_1 = \frac{E^2 R_L}{|Z_l + 2Z_{12}|^2}$. The maximum value of the power is achieved with compensation of the reactive impedance in the denominator $\mathrm{Im}Z_L = -2\mathrm{Im}Z_{12} - \mathrm{Im}Z_{11}$. Solution of the optimization problem $\max_{(R_L)} P_1(R_L)$ gives the values of the optimum load resistance $\mathrm{R}_{L\mathrm{opt}} = \mathrm{Re}Z_{11} + 2\mathrm{Re}Z_{12}$.

In the more general case of several antennas, optimization of the load impedances is performed by numerical method (using the *fminsearch* function in the MatLab). It should be noted that in order to obtain achievable values of the load impedances, it is necessary to introduce constraints. The real part of the impedances be nonnegative. To finding an optimum close to the global optimum, the value obtained at the previous step of calculating the dependence is chosen as the initial value of the impedances.

Optimization of the load impedance was carried out for various values of load impedances
– without the mutual influence of antenna elements; for all elements impedance is equal to $Z_{L0} = 73.1 - j42.5\Omega$; the solid line graphic in Fig. 2;
– with the mutual influence of the antenna elements in the form of thin vibrators; for all elements the impedances is equal to $Z_{L0} = 73.1 - j42.5\Omega$; the dashed line graphic in Fig. 2;
– with the mutual influence of the antenna elements in the form of thin vibrators, the impedances were obtained as a result of optimization by the numerical method in the MatLab; the dotted line graphic in Fig. 2.



a) $NF = 0.4$ dB b) $NF = 10$ dB

Fig. 2. Signal-to-interference ratio

Figure 2 shows the dependence of the signal-to-interference ratio on the interelement distance AA. The number of elements $N = 4$, number of interference $M = 3$, signal-to-noise ratio is equal to $q_s = \frac{D_S/73.1}{kT\Delta f} = 1$, interference-to-noise ratio $q_I = \frac{D_I/73.1}{kT\Delta f} = 100$ for each of interference, frontend noise factor $NF = 0.4$

dB. Angular interference positions were $-35^0, 20^0, 70^0$, direction of the arrival of the signal is perpendicular to the plane of the AA elements placement.

Benefits $5 \ldots 8$ dB of the gain in relation to the signal interference were obtained as a result of optimization of load impedances. The benefits from the load impedances optimization are especially noticeable for small distances between AA elements $d/\lambda = 0.1, \ldots, 0.3$. With an increase of the frondend noise factor, the gain from optimizing the spatial structure decreases and it is significant (Fig.2.) With a decrease in the frontend noise figure, the *fminsearch* optimization procedure is unstable (there is not well-defined optimum). For the technical implementation of the optimal matching principle, it is necessary to know the dependence of the load impedances on the operating conditions of the AA. Figure 3 shsows the dependence of the norm of the difference on the load impedance vector and the value Z_{L0} the distance between the AA ($NF = 0.4$ dB). Increasing the noise figure $NF > 10$ dB enhances optimization process stability. The value of load impedance approaches to Z_{L0}.

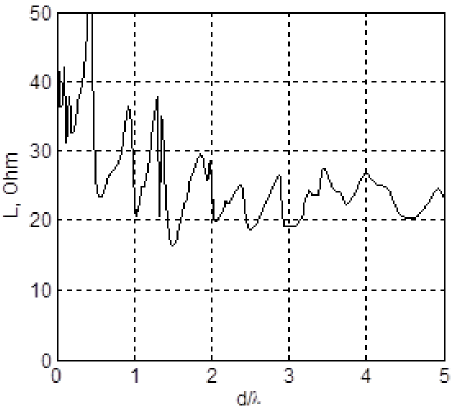


Fig. 3. The norm of the load impedance difference ($NF = 0.4$ dB)

4 Conclusions

The multi channel information system with active antenna array is investigated. As a result of the research, it was established that the matching impedance of the load has a great influence onto increasing the noise immunity of signal processing in the antenna array with mutual influence of the elements. The calculations for the antenna array in the form of thin vibrators (with small distances between) show a gain from the optimization of the load impedance of $5 \ldots 8$ dB. This should be taken into account when performing optimization of the spatial structure of the multi channel information system involving of heavily filled antenna arrays.

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