

# Mutual-Coupling-Aware Optimization of Antenna Element Positions for Electromagnetic Field Focusing

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**ABSTRACT:** This study investigates the optimization of a linear antenna array for maximizing the electric-field amplitude at a prescribed receiving point while accounting for mutual coupling between array elements. Mutual coupling is characterized by transmission coefficients between radiators and incorporated into the calculation of the resulting electric field distribution. The analysis shows that coupling between array elements modifies the field distribution and reduces the electric-field amplitude in the intended antinode region. To mitigate this effect, we propose an optimization approach in which the radiator positions are adjusted to reduce mutual coupling while maintaining a physically feasible array configuration. A genetic algorithm (GA) is used to determine the optimized radiator coordinates, with constraint functions introduced to satisfy the geometrical and physical requirements of the antenna system. The proposed formulation is not limited to genetic algorithms and can be applied with other optimization methods. The results demonstrate that the optimized radiator arrangement reduces mutual coupling and increases the electric field amplitude at the prescribed receiving point compared with the initial array configuration. Theoretical predictions are supported by mathematical modeling and validated by full-wave electromagnetic simulations in CST Studio Suite.

## 1. INTRODUCTION

Controlling the distribution of an electric field within a given space is a key challenge in microwave technology and wireless communications. In particular, forming multiple local electric-field maxima may be necessary for efficient wireless communication in confined spaces. Such problems can arise when a large number of subscriber devices are located within a confined space. Devices operating in the same frequency range interfere with each other, leading to reduced data transfer rate in such networks [1, 2]. Such problems also arise in medical applications. Forming local electric-field maxima in specific spatial regions will improve the signal-to-noise ratio (SNR), leading to increased data transfer rates in wireless networks. However, forming multiple local electric-field maxima and minima is achieved using multiple antenna radiators [3, 4]. Any radiating antenna not only radiates in the forward direction but also exhibits lateral radiation, related to both the main-lobe width of the radiation pattern and the side-lobe level [5–7]. The mutual influence of antenna radiators in a system that forms a local maximum of the electric field will change the electric-field strength at antenna locations, which may affect the final result [8–12] and lead to distortion of the electric-field distribution compared to the target.

The purpose of the present study is not to establish the superiority of the genetic algorithm over other optimization techniques. The optimization method is used here to demonstrate the proposed electromagnetic formulation of the radiator-position problem. Consequently, numerical results obtained in studies devoted to other optimization criteria cannot be directly

compared with the present results solely based on the optimization algorithm used. A meaningful algorithm-to-algorithm comparison would require identical antenna configurations, objective criteria, constraints, and computational conditions. Such a benchmark is outside the scope of the present work.

Therefore, this study investigates whether varying the positions of radiating antennas can improve the resulting electric-field distribution.

### 1.1. Mathematical Model of the System for Free Space

Forming a local electric-field maximum in a given spatial region allows increasing the signal-to-noise ratio (SNR) at the subscriber device's receiving antenna. The method consists of  $N$  emitting antennas positioned spatially. A receiving point (Rx) is also positioned spatially. Figure 1 shows an example of the arrangement of emitting antennas and the receiving point. The required electric-field amplitude was set at the receiving point. Next, the complex transmission coefficients between each transmitting antenna and the receiving point were determined. By solving a system of linear algebraic equations

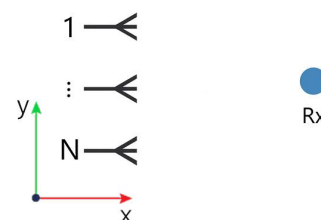


**FIGURE 1.** A system that forms a local maximum of the electric field.

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(SLAEs), the signals' complex amplitudes that must be applied to each transmitting antenna to obtain the required electric-field distribution in space were determined. The effectiveness of this method has been demonstrated in several studies [3, 4].

Based on [3, 4], we recall a system that generates a local maximum in the electric-field amplitude. The origin of this system is at the geometric center of the space. The  $X$  and  $Y$  coordinate axes are oriented relative to the antenna array positioning directions and the receiving point. The  $Z$  axis points upward.

Let us recall [3, 4] designating the complex amplitudes of radiated signals:

$$a_n = |a_n| \cdot e^{j \cdot \phi_n}, \quad (1)$$

where  $|a_n|$  is the amplitude of the signal radiated from  $n$ -th antenna;  $n$  is the initial phase of the signal radiated from the  $n$ -th antenna;  $j$  is the imaginary unit.

Complex amplitude at the reception point:

$$b_1 = |b_1| \cdot e^{j \cdot \Psi_1}, \quad (2)$$

where  $|b_1|$  is the signal amplitude at the 1st reception point, and  $\Psi_1$  is the signal phase at the 1st reception point.

The set of complex amplitudes of signals at radiation points forms a column vector of radiated signals  $A$ , and the set of complex amplitudes of signals at the reception point forms a unit column vector of received signals  $B$ .

The system shown in Figure 1 is represented as a multiport microwave (see Figure 2) [3, 4]. The number of multiport inputs is  $N + 1$ , where  $N$  is the number of emitting antennas and one receiving point. Obviously, inputs 1 through  $N$  correspond to the emitting antennas, and input  $N + 1$  corresponds to the receiving point.

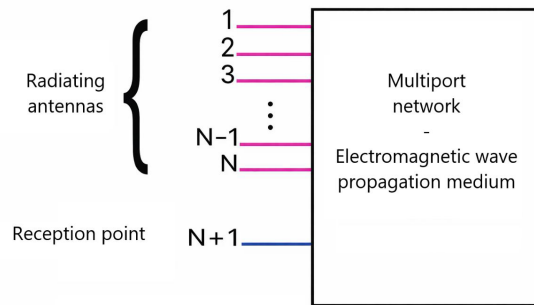


**FIGURE 2.** Representation of a system that forms a local maximum of the electric field in the form of a microwave multiport network [3, 4].

Therefore, by specifying the column vector of output signals of the multiport network  $[Y]$ , one can determine the column vector of input signals  $[X]$ . They are connected by a scattering matrix ( $S$ -parameters —  $[S]$ ):

$$[Y] = [S] \cdot [X], \quad (3)$$

Let's set boundary conditions. Considering that forming a local maximum of the electric field is required within the room, not at its boundaries, the elements of the column vector  $[Y]$  from 0 to  $N$  will be equal to zero. Element  $N+1$  determines the complex amplitude of the signal ( $b_1$ ) at a given receiving point.

$$[Y] = [y_1 = 0; \dots; y_N = 0; y_{N+1} = b_1]^T. \quad (4)$$

It is also assumed that in the  $[X]$  input signal (influence) column vector, the element with  $N+1$  is equal to zero. A simplification is specified, indicating that there is no reflection at the point in question.

$$[X] = [x_1 = a_1; \dots; x_N = a_N; x_{N+1} = 0;]^T. \quad (5)$$

The  $S$ -parameter matrix of the multiport network has the following form [3, 4]:

$$[S] = \begin{bmatrix} s_{1,1} & \dots & s_{1,N} & s_{1,N+1} \\ \vdots & \vdots & \vdots & \vdots \\ s_{N,1} & \dots & s_{N,N} & s_{N,N+1} \\ s_{N+1,1} & \dots & s_{N+1,N} & s_{N+1,N+1} \end{bmatrix}. \quad (6)$$

The matrix's diagonal elements are the reflection coefficients from the multiport's corresponding inputs. The matrix's off-diagonal elements are the transmission coefficients between the multiport's corresponding inputs.

In free space, transmission coefficients are determined by the following expression [3, 4]:

$$s_{i,k} = F_{i,k} \cdot F_{k,i} \cdot r_{i,k}^{-q} \cdot \exp(-j \cdot \beta \cdot r_{i,k}), \quad (7)$$

where  $r_{i,k}$  is the distance from the point corresponding to the  $i$ -th input of the multiport network to the point corresponding to the  $k$ -th input of the multiport network;  $\beta = \frac{2 \cdot \pi}{\lambda}$  is the phase coefficient;  $F_{i,k}$  is the element of the matrix containing the field gain coefficients of the antenna installed at the point corresponding to input  $k$  in the direction of the point corresponding to input  $i$ ; factor  $r_{i,k}^{-q}$  determines the decrease in the amplitude of the electromagnetic-wave strength during propagation from the point corresponding to the input of the multiport  $i$  to the point corresponding to the input of the multiport  $k$ . For the electric field in the near zone,  $q = 2$ ; for the electric field in the far zone,  $q = 1$ .

The distance between inputs of the multiport network is determined by the following expression [3, 4]:

$$r_{i,k} = \sqrt{(x_i - x_k)^2 + (y_i - y_k)^2 + (z_i - z_k)^2}, \quad (8)$$

where  $(x_i, y_i, z_i)$  — Cartesian coordinates of the  $i$ -th point.

The set of multiport inputs that are radiating antennas can be analyzed as an antenna array. Accordingly, when calculating the transmission coefficients using expression (7), it is necessary to determine in which zone of the antenna array the multiport input for which the transmission coefficient is calculated is located in order to correctly select the value of  $q$ . The following expression from [5] is used to determine the boundaries of the near-zone region:

$$r_{nf} \leq \frac{2 \cdot D^2}{\lambda}, \quad (9)$$

where  $D$  is the aperture size of the antenna array.

Thus, we can write the condition for determining the value of  $q$ :

$$q = \begin{cases} 2, & r_{i,k} \leq \frac{2 \cdot D^2}{\lambda} \\ 1, & r_{i,k} > \frac{2 \cdot D^2}{\lambda} \end{cases} \quad (10)$$

The free-space model is used as a controlled reference environment that allows the effects associated with radiator positions and mutual interaction to be considered separately from additional propagation phenomena. Accordingly, the numerical results obtained with this model should not be interpreted as a complete representation of a particular indoor propagation environment.

## 1.2. Decomposition Analysis of the $S$ -Parameter Matrix of a Multiport Network

In [3, 4], it is shown that the matrix of  $S$ -parameters (6) of a multiport network can be divided into submatrices:

$$[S] = \begin{bmatrix} [S_{TT}] & [S_{TR}] \\ [S_{RT}] & [S_{RR}] \end{bmatrix}, \quad (11)$$

where  $[S_{TT}]$  is the submatrix that determines transmission coefficients from one radiation point to another (submatrix of mutual transmission coefficients), with dimensions  $[N \text{ rows}; N \text{ columns}]$ ;  $[S_{TR}]$  is the submatrix defining transmission coefficients from the receiving point to the transmitting point (submatrix of inverse transmission coefficients), with dimensions  $[N \text{ rows}; 1 \text{ column}]$ ;  $[S_{RT}]$  is the submatrix defining transmission coefficients from the emission point to the reception point (submatrix of direct transmission coefficients), with dimensions  $[1 \text{ row}; N \text{ columns}]$ ;  $[S_{RR}]$  is the submatrix defining the reflection coefficient from the receiving point, with dimensions  $[1 \text{ row}; 1 \text{ column}]$ .

Figure 3 [3, 4] shows a schematic representation of the role of the submatrices.

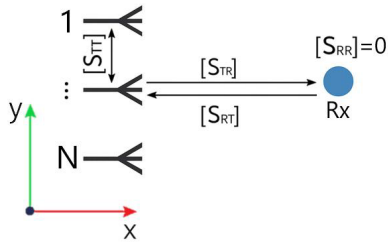


FIGURE 3. Schematic representation of the role of submatrices [3, 4].

Let us examine the submatrices in more detail. For the  $[S_{TT}]$  submatrix, the diagonal elements are the reflection coefficients from the inputs of the radiating antenna. The off-diagonal elements are complex transmission coefficients between the multiport's corresponding transmitting inputs (radiating antennas):

$$[S_{TT}] = \begin{bmatrix} s_{1,1} & \dots & s_{1,N} \\ \dots & \dots & \dots \\ s_{N,1} & \dots & s_{N,N} \end{bmatrix}, \quad (12)$$

The elements of the submatrix  $[S_{TR}]$  are complex transmission coefficients from the receiving point to the transmitting point:

$$[S_{TR}] = \begin{bmatrix} s_{1,N+1} \\ \dots \\ s_{N,N+1} \end{bmatrix}, \quad (13)$$

where  $s_{N,N+1}$  is the transmission coefficient from the receiving point with number  $N+1$  to the emission point with number  $N$ . The submatrix  $[S_{TR}]$  consists only of transmission coefficients.

All elements of the submatrix  $[S_{RT}]$  are transmission coefficients from the transmission point to the reception point:

$$[S_{RT}] = [s_{N+1,1} \quad \dots \quad s_{N+1,N}], \quad (14)$$

where  $s_{N+1,N}$  is the transmission coefficient from transmission point  $N$  to reception point  $N+1$ . The submatrix  $[S_{RT}]$  consists only of the transmission coefficients from the transmitting point to the receiving point.

The  $[S_{RR}]$  submatrix element is the reflection coefficient from the receiving antenna input. A simplification is given that there is no reflection from the receiving antenna input:

$$[S_{RR}] = s_{N+1,N+1} = 0. \quad (15)$$

In the ideal case, when all receiving and transmitting antennas are matched, and there is no mutual influence between transmitting and receiving points, expression (3) takes the form:

$$[B] = [S_{RT}] \cdot [A], \quad (16)$$

Subsequently, the number of equations is reduced from  $N+1$  to 1.

In practice, such simplification is not always possible. Specifically, antenna radiators in the system may interfere with each other. This can lead to deviations in the electric-field strength at locations of the transmitting antennas. This, in turn, can lead to changes in the electric-field strength at the receiving points.

## 1.3. Analysis of $S_{TT}$ Submatrix

The  $[S_{TT}]$  submatrix contains mutual transmission coefficients between radiators, and the diagonal elements of this submatrix contain the reflection coefficient from the input of each antenna.

Considering the boundary conditions specified in Section 1 and in [3, 4], it is known that in the column vector of output complex amplitudes  $[Y]$ , elements from 1 to  $N$  are equal to zero (4), because when forming a local maximum of the electric field in a given region of space, the task is to form a local maximum in the volume of the room, and not at its boundaries.

The column vector of radiated  $[X]$  signals (the column vector of the effect) contains an element  $N+1$  equal to zero (5), and it is considered that the point under consideration at which a local maximum of the electric field is formed does not reflect the signal.

Considering the given  $[Y]$  and  $[X]$ , it can be seen that the elements of matrices  $[S_{TR}]$  and  $[S_{RR}]$  are multiplied by zeros in the column vector of radiated signals; therefore, we can write:

$$[Y] = \begin{bmatrix} [S_{TT}] \\ [S_{RT}] \end{bmatrix} \cdot [A], \quad (17)$$

where  $[A] = [a_1; \dots; a_N]^T$  — column vector of complex amplitudes of radiated signals.

Expression (17) can be represented in the form of two SLAEs:

$$[0] = [S_{TT}] \cdot [A], \quad (18)$$

$$real[B] = [S_{RT}] \cdot [A], \quad (19)$$

where  $[B] = [b_1]^T$  — unit column vector of the complex amplitude of signals at the reception point.

The system of linear algebraic equations (19) is solved to determine the column vector of radiated signals  $[A]$ . The system of linear algebraic equations (18) determines the absence of mutual influence between the radiators. It can be used as a quantitative measure of mutual influence for a given  $[S_{TT}]$  and  $[A]$ , obtained by solving (19). On the one hand, violating any of equalities indicates mutual influence between the antennas and can lead to changing the electric-field strength at the receiving point. On the other hand, this system can be used to determine the position of the radiators at which their mutual influence is minimal. In other words, it does not exceed a certain specified value. This is an optimization problem whose objective function is based on Equation (18).

Expression (18) can be used as a quantitative measure of how much the calculation result deviates from zero. The closer the result is to zero, the less the mutual influence is.

To account for mutual coupling between antenna radiators in the system, it is necessary to calculate the transmission coefficient between each pair of antennas. To do this, we write the expression:

$$S_{TT}^{(i,k)} = F_{i,k} \cdot F_{k,i} \cdot r_{i,k}^{-q} \cdot \exp(-j \cdot \beta \cdot r_{i,k}), \quad (20)$$

where  $F_{i,k}$  and  $F_{k,i}$  are the antenna field gain coefficients defined above;  $\beta$  is the phase coefficient;  $r_{i,k}$  is the distance between the antennas.

In the considered optimization problem, mutual-transmission coefficients depend on spatial positions of the radiating elements. Because these positions vary during optimization, the corresponding interaction coefficients must also be recalculated for each antenna configuration. In the present study, an analytical representation is used to provide this coordinate-dependent recalculation in a consistent mathematical model.

From expression (20), it is clear that the greatest influence will be exerted by antennas close to each other (antennas radiate in the same direction). Although radiation to neighboring antennas can occur through side lobes ( $F_{i,k} \cdot F_{k,i} \ll 1$ ), which reduces the magnitude of interaction, the small distance  $r_{i,k}^{-q}$  between neighboring antennas does not allow the amplitude of the electric field strength to decrease significantly.

The radiation pattern of each element can be specified in tabular form, or an approximating function can be used. In the former case, the radiation pattern can be measured for a real antenna or obtained as a result of simulation. In the latter case, typical functions for approximating the main lobe of the radiation pattern can be used [13–16]: isotropic radiation pattern,  $\text{sinc}(x)$ , Gaussian curve, and  $\cos^n(\theta)$ .

- Isotropic radiation pattern. Ideal radiation pattern with uniform radiation in all directions.

$$F_{\text{isotropic}}(\alpha; \theta) = 1, \quad (21)$$

- The  $\text{sinc}(x)$  function [13–16] allows you to obtain not only the main lobe, but also side lobes.

$$F_{\text{sinc}}(\alpha; \theta) = \begin{cases} \left| \frac{\sin(x(\alpha; \theta))}{x(\alpha; \theta)} \right|; & x \neq 0 \\ 1; & x = 0 \end{cases}, \quad (22)$$

where  $x(\alpha; \theta) = \frac{2 \cdot \rho_0}{\Theta_{3\text{dB}}} \cdot \psi(\alpha; \theta)$ ,  $\psi(\alpha; \theta) = \arccos(\cos \alpha \cdot \cos \theta)$  is the angle between the antenna normal and the radiation direction under consideration (radians);  $\alpha$  is the azimuth;  $\theta$  is the elevation angle;  $\rho_0 = 1.3916$  is the positive solution of the equation  $|\frac{\sin x}{x}| = \frac{1}{\sqrt{2}}$ ;  $\Theta_{3\text{dB}}$  is the width of the main lobe of

the radiation pattern at the level of 0.707 (−3 dB).

- Gaussian approximation [13–16] allows obtaining a smooth radiation pattern without side lobes.

$$F_{\text{gauss}}(\alpha; \theta) = \exp(-(\sigma \cdot \psi(\alpha; \theta))^2), \quad (23)$$

where  $\psi(\alpha; \theta) = \arccos(\cos \alpha \cdot \cos \theta)$  is the angle between the antenna normal and the direction under consideration (radians);  $\alpha$  is the azimuth;  $\theta$  is the elevation angle;  $\sigma =$

$\frac{\sqrt{2 \ln 2}}{\Theta_{3\text{dB}}}$  determines how quickly the radiation pattern falls off (standard deviation);  $\Theta_{3\text{dB}}$  is the main lobe width at −3 dB (radians).

- In  $\cos^n$  — approximation, the main-lobe shape is determined by a power function of the deflection angle [13–16].

$$F_{\cos}(\alpha; \theta) = \begin{cases} \cos^n(\psi(\alpha; \theta)); & \psi < \frac{\pi}{2} \\ 0; & \psi > \frac{\pi}{2} \end{cases}, \quad (24)$$

where  $\psi(\alpha; \theta) = \arccos(\cos \alpha \cdot \cos \theta)$ ;  $\alpha$  is the azimuth;  $\theta$  is the elevation angle;  $n$  determines the rate of decay of the radiation pattern.

It is worth noting that these are only four of the most commonly used methods for approximating the radiation pattern of antenna radiators [7, 17]. By calculating the transmission coefficients between radiating antennas, it is possible to determine their mutual influence.

If there is coupling between antenna radiators in the system, it is expected that adjacent antenna radiators will change the electric-field strength at emission points, due to the matrix of mutual transmission coefficients  $[S_{TT}]$ , which describes mutual coupling between emitting antennas. The  $S$ -parameter matrix (6) describes relationships among all ports of the multi-port network, and the submatrix (12) describes the mutual coupling between radiating elements. The complex amplitude of the electric-field strength at the  $i$ -th radiation point, created by all elements except the  $i$ -th, is equal to the linear sum of their contributions (29).

The column vector of received signals  $[Y]$  will contain not only the signals' complex amplitudes at a given reception point, but also the complex amplitudes at emission points. Then, expression (4) will take the following form:

$$[Y] = [y_1 = c_1; \dots; y_N = c_N; y_{N+1} = b_1]^T = [[C]; [B]]^T \quad (25)$$

where  $c_n$  is the signal's complex amplitude at the location of the  $n$ -th antenna;  $b_1$  is the signal's complex amplitude at the reception point;  $[C]$  is a column vector containing the signals' complex amplitudes at the locations of the radiating antennas;  $[B]$  is a unit column vector of the signal's complex amplitude at the reception point.

Thus, taking into account the mutual influence of radiating antennas on each other, expression (18) can be represented as:

$$[C] = [S_{TT}] \cdot [A]. \quad (26)$$

Let us consider the change in the amplitude of the electric-field strength at the receiving point from a mathematical point of view. From [3, 4], the expression for calculating the  $k$ -th element of the column vector of the output electromagnetic waves using the full matrix of  $S$ -parameters has the form:

$$y_k = \underbrace{s_{k,1} \cdot x_1 + s_{k,2} \cdot x_2 + \dots + s_{k,N} \cdot x_N}_{[S_{TT}], k \leq N} + \underbrace{s_{k,N+1} \cdot x_{N+1} + s_{k,N+2} \cdot x_{N+2} + \dots + s_{k,N+M} \cdot x_{N+M}}_{[S_{RR}], k > N} \quad (27)$$

At first glance, it may appear that when calculating the electric field strength at the  $k$ -th receiving point ( $k > N$ ), the matrix  $[S_{TT}]$  does not participate in forming the value  $y_k$ . However, this is not the case because the matrix  $[S_{TT}]$  influences the calculation of the complex amplitudes of signals  $[X]$  for  $k \leq N$ . The influence on the complex amplitudes of signals  $[X]$  indirectly affects the resulting distribution of the electric field in space.

It is worth noting that the mutual influence of radiating antennas alters the field distribution across the antenna aperture, which in turn distorts the field's spatial distribution. This is because to radiate an electromagnetic wave from an antenna, the transmitter generates and transmits a signal with the required complex amplitude; that is, it generates its own electromotive force (EMF). Owing to the mutual influence, the electromagnetic wave incident on the antenna from an adjacent antenna induces an additional EMF on the antenna, which, according to the principle of superposition, is added to the antenna's own EMF. Not only does the amplitude of the radiated signal change, but also its initial phase. This changes the complex amplitude of the radiated signal, altering the spatial distribution of the electric field. For each specific antenna with serial number  $n$ , the total EMF induced by all other antennas is determined by the coefficient  $c_n$ .

The values of the elements of column vector  $[C]$  can be used as a numerical measure of the mutual influence of adjacent antenna radiators. For brevity, the measure of the mutual influence of adjacent antenna radiators will henceforth be referred to as the mutual influence of antennas.

The magnitude of the mutual influence of antennas can be changed either by adjusting the complex amplitudes of radiated

signals so that their field contributions cancel at the antenna locations or by varying the elements of the matrix  $[S_{TT}]$ .

A change in the complex amplitudes of radiated signals will, in addition to the mutual compensation of electromagnetic waves at the antenna locations, lead to possible distortions of the generated distribution of electric-field strength in space.

The second approach involves varying element values of the  $[S_{TT}]$  matrix. This can be accomplished by moving the radiators in space to reduce their mutual influence.

Let's consider several quality criteria for compensating antennas' mutual influence:

- **Minimax criterion.** The goal is to minimize the maximum antenna interference. Mathematically, it is expressed as  $\min(\max |c_i|)$ , which means that the maximum value from column vector  $[C]$  must not exceed the required value.
- **Minimizing the root-mean-square (RMS) deviation of the elements of column vector  $[C]$ .** Minimizing the RMS will minimize the spread of the elements of column vector  $[C]$  relative to the mean. Mathematically, the condition for minimizing the RMS is expressed as follows (the modulus is used to account for only the amplitude component):

$$\min(\sigma_C) = \min \left( \sqrt{\frac{1}{N} \sum_{i=1}^N (|c_i| - \mu_C)^2} \right), \quad (28)$$

where  $\mu_C = \frac{1}{N} \sum_{i=1}^N |c_i|$  is the mathematical expectation.

When a local electric-field maximum is formed, the antenna configuration is excited by signals with complex amplitudes  $a_n = |a_n| \cdot \exp(j \cdot \phi_n)$ . Consequently, the magnitude of the antennas' mutual influence is determined by

$$c_i = \sum_{k=1}^N (s_{i,k} \cdot a_k), \quad (29)$$

From expression (29), the magnitude of antennas' mutual influence can be determined for a specific field configuration in space. This assessment allows for considering constructive and destructive interference at the antenna locations, which allows the precise determination of the electric field amplitude at the locations of radiating antennas.

Based on the above, we propose an algorithm for searching optimal positions of radiating antennas, which allows positioning antenna radiators in the system such that the magnitude of their mutual influence (mutual transmission coefficient) does not exceed a given value.

It is proposed to perform multi-criteria optimization of antenna placement using the following algorithm:

1. A criterion for the quality of antenna mutual influence is selected. The problem  $|c_i| \rightarrow \min$  for  $(\Delta x_n; \Delta y_n; \Delta z_n) \rightarrow \min$  is solved; that is, it is necessary to ensure the minimum possible mutual influence with the minimum possible antenna displacement in the system. This requirement is related to the fact that as the distance between radiators in the antenna array increases, diffraction lobes appear [5–7, 18, 19]. In addition, in

the works [4, 20], it is shown that an increase in the distance between the antenna array and the focal point leads to the fact that the dimensions of the zone of high electric-field strength expand and shift relative to the given value by a distance that is associated with the ratio of the linear dimensions of the antenna array ( $D$ ) to the distance to the focal point ( $F$ ) —  $(D/F)$ . Thus, a non-strict recommendation can be written:  $|c_i| \rightarrow \min$  for  $(\Delta x_n; \Delta y_n; \Delta z_n) \lesssim \lambda$ . In other words, the change in antenna coordinates relative to the preliminary coordinates should be less than or equal to the wavelength to position the local maximum of the electric field in the required region of space.

2. The preliminary coordinates of the radiators

$(x_n^{(0)}; y_n^{(0)}; z_n^{(0)})$ , the parameters of the radiation pattern of the radiators  $F_{i,k}$ , the coordinates of the reception point  $(a_1; b_1; c_1)$ , and the value  $[B]$  of the unit column vector of the complex amplitude at the reception point are specified.

3. Set restrictions on the range of coordinates along each axis within which it is possible to change the coordinates of the radiators  $[x_{\min}; x_{\max}]$ ,  $[y_{\min}; y_{\max}]$ ,  $[z_{\min}; z_{\max}]$ .

4. Calculate the element values of the matrix  $[S_{TT}]$  using expression (20), taking into account the type of radiation pattern of the radiating antenna, for example, using one of the expressions (21)–(24).

5. Perform calculations using expression (17), which will provide values of the column vector  $[A]$ , considering the influence of the matrix  $[S_{TT}]$ .

6. Perform calculations using expression (26) to determine the column vector  $[C]$ . Check whether the condition specified in the first paragraph is met according to the quality criterion. If the condition, according to the quality criterion, is met, the algorithm terminates. If it is not met, the algorithm continues.

7. Operation of the optimization algorithm.

8. If the algorithm is successfully completed, new coordi-

nates of the antenna radiators  $(x_n^{(\text{new})}; y_n^{(\text{new})}; z_n^{(\text{new})})$  will be obtained, with which the condition for the specified quality criterion will be met.

Figure 4 shows a simplified block diagram of the algorithm for optimizing the location of antenna radiators.

An optimization algorithm for determining the new coordinates of radiating antennas can be implemented using different numerical methods. In the proposed work, a genetic algorithm was selected as a population-based search tool suitable for handling a multidimensional coordinate space and the imposed positional constraints. The choice of the genetic algorithm (GA) was intended to demonstrate the proposed optimization procedure and does not imply its superiority over alternative optimization methods [21–25].

The genetic optimization method operates by randomly selecting, combining, and varying desired parameters using mechanisms similar to natural selection. It works with an entire population of solutions by combining and mutating them, which explores different regions of the search space. The population-based structure of the genetic algorithm also allows individual solution evaluations to be parallelized. Its disadvantages include increased computing power requirements.

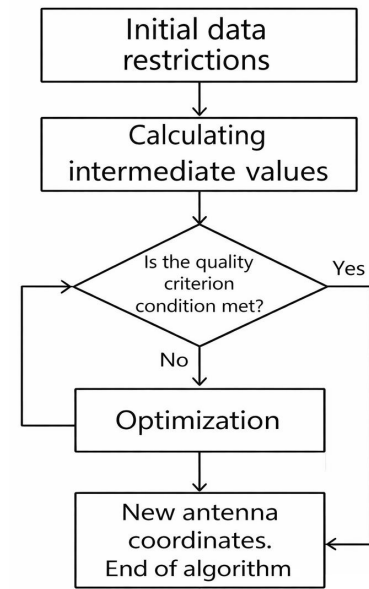


**FIGURE 4.** Block diagram of the algorithm for optimizing the location of antenna radiators.

## 2. APPLICATION OF PENALTY METHODS IN CALCULATING NEW COORDINATES OF ANTENNA RADIATORS

Optimizing the location of antenna radiators in a system that generates the required electric field distribution in space must have a number of operational constraints. This is because the optimization algorithm searches for new antenna radiator coordinates based on a specified criterion for the mutual influence of the emitting antennas. One of the key concepts of wireless communication is the ability to transmit information to the desired receiving point while remaining at a certain distance from it; therefore, placing antenna radiators close to the receiving point may not be the best solution.

When optimizing a linear antenna array, one optimization axis is used, along which radiators are located; in this case, the algorithm cannot bring radiators and receiving points closer together.

Let us describe the first constraint, which is the prohibition of proximity to the receiving point. This is required because, as a rule, antennas must be positioned at a certain distance, and the absence of such a constraint would result in the antennas moved close to the receiving point. Let's write down the condition for this constraint:

$$\|Ant_i - Receiver\| \geq \|Ant_i^{(0)} - Receiver\|, \quad (30)$$

where  $Ant_i^{(0)} = (x_i^{(0)}; y_i^{(0)}; z_i^{(0)})$  is the initial coordinates of the  $i$ -th antenna;  $Ant_i = (x_i; y_i; z_i)$  is the new antenna coordinates obtained during the optimization process;  $Receiver = (x; y; z)$  is the coordinates of the reception point;  $\|Ant - Receiver\|$  is the operation of calculating the distance between the coordinates of two points. This can be rewritten as follows:

$$\Psi_i^{\text{receiver}}(x; y; z) = \|Ant_i^{(0)} - Receiver\|$$

$$- \|Ant_i - Receiver\| \leq 0, \quad (31)$$

Another unpleasant aspect is the disruption of the radiators' linear arrangement. This occurs when, as a result of optimization, the antennas can be positioned one behind the other.

As a result of this antenna arrangement, one antenna may radiate directly toward the antenna positioned in front of it. In practice, this creates difficulties when designing indoor wireless networks, where antennas must be positioned along a wall. This result from the optimization algorithm is unsatisfactory and requires further refinement. By optimizing the radiator placement of a single linear antenna array along the radiator axis, this problem is eliminated.

Let's write down the second constraint: a prohibition on antennas coming close together. The optimization algorithm may cause the antennas to become too close, in the same coordinates or one behind the other, which would have negative consequences for the antenna system, which generates a specific electric-field distribution in space. Similarly, to (30)–(31), we write the prohibition condition for antennas coming close together:

$$\Psi_{i,n}^{\text{antennas}}(x; y; z) = \|Ant_i^{(0)} - Ant_n^{(0)}\| - \|Ant_i - Ant_n\| \leq 0, \quad (32)$$

It is also worth noting that when a wireless network is implemented indoors, the placement of antennas along the wall to avoid cluttering the interior space with a chaotic antenna arrangement is an important factor. Therefore, the antenna placement constraint along a given line (wall) can be expressed as follows:

$$\Psi_{i,L}^{\text{line}}(x; y; z) = r_{i,L} - \zeta_L \leq 0, \quad (33)$$

where  $r_{i,L}$  is the distance from the  $i$ -th antenna to the  $L$ -th line, and  $\zeta_L$  is the antenna's maximum permissible position along the line.

The objective function, taking into account the introduced restrictions, will take the form:

$$\begin{aligned} \chi(x; y; z)_{\text{penalty}} &= \chi(x; y; z)_{\text{target}} + \mu_{\text{receiver}} \cdot \sum_{i=1}^N [\max \{0, \Psi_i^{\text{receiver}}(x; y; z)\}]^2 \\ &+ \mu_{\text{antennas}} \cdot \sum_{1 < i < n \leq N} [\max \{0, \Psi_{i,n}^{\text{antennas}}(x; y; z)\}]^2 \\ &+ \mu_{\text{line}} \cdot \sum_{1 < i \leq L} [\max \{0, \Psi_{i,L}^{\text{line}}(x; y; z)\}]^2 \end{aligned} \quad (34)$$

where  $\mu_{\text{receiver}}$ ,  $\mu_{\text{antennas}}$ , and  $\mu_{\text{line}}$  are penalty coefficients.

The function  $\max\{0, \Psi(x; y; z)\}$  is defined piecewise as follows:

$$\begin{cases} \max\{0, \Psi(x; y; z)\} = 0; & \Psi(x; y; z) \leq 0 \\ \max\{0, \Psi(x; y; z)\} = \Psi(x; y; z); & \Psi(x; y; z) > 0 \end{cases} \quad (35)$$

### 3. GENETIC OPTIMIZATION METHOD

In this study, the GA is considered an optimization tool rather than the principal scientific contribution. The main objective is to formulate and demonstrate an approach, in which the positions of the radiating elements are varied to reduce their mutual interaction while satisfying the imposed geometrical constraints. The proposed optimization procedure is not inherently associated with the genetic algorithm. Other optimization methods can be used within the same framework provided that they operate with the same objective criterion and positional constraints. The GA was selected as a convenient population-based method capable of searching a multidimensional coordinate space without requiring an explicit analytical form of the optimum solution.

The genetic method is a heuristic method for searching the location of radiating antennas based on given constraints and a criterion for the quality of the mutual influence of antennas, which is inspired by the natural evolution of biological species [26, 27].

The main steps of the genetic algorithm are as follows:

1. A population of individuals represents different points in the search space.
2. Each individual is encoded by a chromosome vector.
3. Each individual is assigned a fitness value. The higher the value of  $\gamma(v)$  is, the more adapted the individual is.
4. The population goes through evolutionary cycles:
  - Selection is the probabilistic selection of prototype individuals such that the fittest have a better chance of leaving offspring.
  - Crossbreeding is mixing genes from two parents to create offspring.
  - Mutation is a random change in genes that maintains diversity.
  - Replacement is forming a new generation.

The evolutionary process continues until the adopted termination condition is satisfied, after which the best feasible individual found during the search is taken as the resulting solution.

The formulation of the problem of optimizing the antenna location will look like:

1. A chromosome is defined. The coordinates of the radiating antennas were collected into a single column vector.

$$[V] = [v_1 = x_1, v_2 = y_1, v_3 = z_1, \dots, v_{3N-2} = x_N, v_{3N-1} = y_N, v_{3N} = z_N]^T \quad (36)$$

2. An objective function is specified. This could be minimizing the maximum of antenna interference (the minimax quality criterion), minimizing the standard deviation of antenna interference, minimizing the sum of squares of antenna interference, etc.

3. The fitness function is written:

$$\gamma(v) = \frac{1}{1 + \chi_{\text{target}}(v) + \xi \cdot \Psi(v)} \quad (37)$$

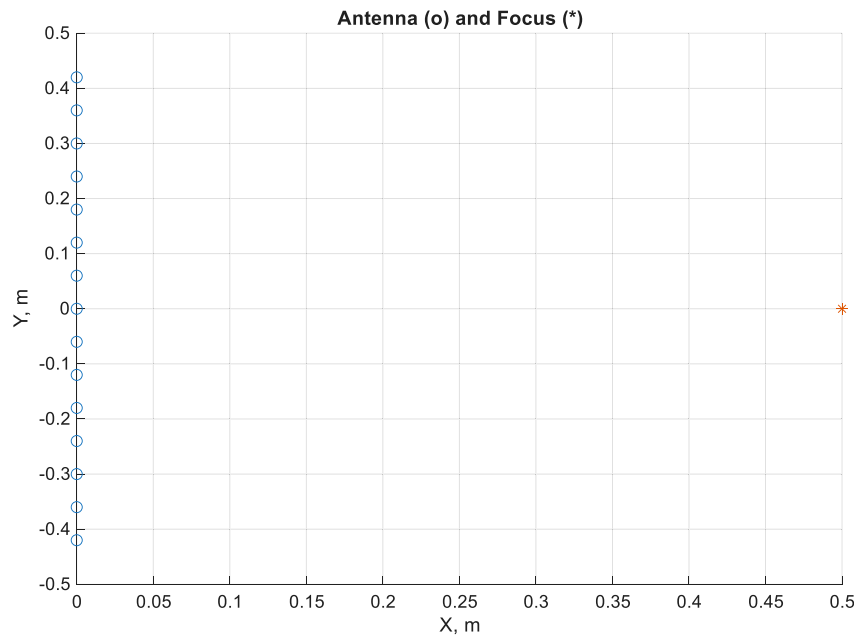


**FIGURE 5.** Location of the radiating antennas and the receiving point in space.

where  $\chi_{\text{target}}(v)$  is the objective function;  $\Psi(v)$  is the penalty function;  $\xi > 0$  is the penalty coefficient.

4. A random selection is made from three random individuals. The selection is based on the fitness function (37). The selected individuals are allowed to crossbreed.

5. Crossing is carried out according to three laws with equal probability:

5.1 Single-point crossover. A point is randomly assigned in the parental genome, dividing it into two halves. One part of the gene is inherited by the first offspring, and the other part is inherited by the second offspring.

5.2 Crossing at two points in the genome. Two points are randomly assigned in the genome of parent individuals, which define boundaries of the inherited gene.

5.3 Uniform crossover. A pseudorandom sequence of zeros and ones is generated. This sequence determines which genes will be inherited by the offspring from the first or second parent.

6. Mutation. Sometimes an optimization problem may have multiple extrema. To prevent the algorithm from getting stuck at a local extremum, a mutation probability  $p_{\text{mut}}$  is introduced. This probability is typically specified for a single gene, not for the entire genome. With probability  $p_{\text{mut}}$ , each coordinate shifts by a value within the range  $[-0.002 \text{ m}; +0.002 \text{ m}]$  with a probability of 95%, and by a value within the range  $[-0.001 \text{ m}; +0.001 \text{ m}]$  with a probability of 68%. This means that the expected shift value is 0, and the shift's standard deviation is 0.001.

7. The principle of elitism. According to the fitness function (37), the top 1–5% of individuals are selected. The elite individual retains the exact coordinate values. It allows the elite individual to additionally enter the tournament and produce offspring. This principle ensures that the best solutions found in the current generation are not lost in the subsequent generation. That is, several fittest individuals are carried over into the next generation unchanged.

In this study, GA was used as a numerical search tool to obtain a feasible antenna configuration, satisfying the selected mutual-interaction criterion and geometrical constraints. The elitist mechanism preserves the best solutions found during the search. Because the algorithm is stochastic, independent runs may generally lead to different coordinate sets, and the proposed work does not claim uniqueness or run-to-run identity of the optimized configuration. The study focuses on the electromagnetic effect of coordinate optimization rather than statistical or convergence properties of the optimizer itself; an analysis of convergence rates and solution variability over multiple independent runs is outside the scope of the present work. To optimize the location of radiating antennas using a genetic algorithm, the penalty functions described in (34) were applied.

#### 4. OPTIMIZATION OF THE LOCATION OF LINEAR ANTENNA ARRAY RADIATORS

Consider a linear antenna array consisting of 15 radiators with an isotropic radiation pattern. The operating frequency is 2.5 GHz, and the distance between radiators is  $\lambda/2$ . The receiving point is located 0.5 m from the geometric center of the antenna array. Figure 5 shows the spatial arrangement of the antennas and receiving point.

The selected number of elements and operating frequency define the particular numerical case considered in this study; consequently, the quantitative results presented below refer specifically to this configuration. The numerical example considers one receiving point, and the results therefore characterize the influence of coordinate optimization for this prescribed receiving location.

The isotropic radiation pattern was used in this numerical example intentionally as a reference case. This choice makes it possible to separate the effect associated with the spatial arrangement of the radiators from the effect introduced by a spe-

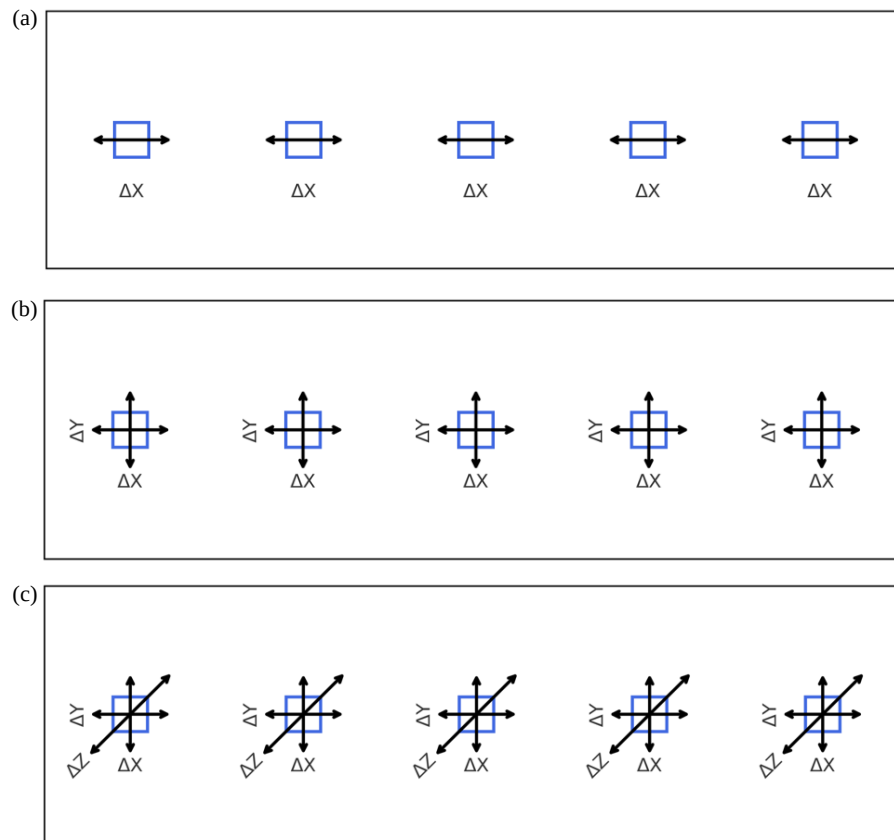


**FIGURE 6.** Optimization options. (a) Movement along one axis, (b) movement along two axes orthogonal to each other, and (c) movement along three axes.

cific directional radiation pattern. The proposed calculation procedure is not restricted to isotropic radiators. As discussed above, the radiation pattern of an individual element can be introduced using analytical approximations, numerical simulation results, or measured antenna characteristics. Therefore, the isotropic array considered below should be regarded as a controlled model used to demonstrate the influence of radiator-coordinate optimization rather than as a representation of a particular practical antenna element.

Let us consider three options for optimizing the location of the radiators of a linear antenna array (optimization will be performed using the minimax quality criterion):

1. Movement of radiators along one axis, along which a linear antenna array is placed (Figure 6(a)).
2. Movement of radiators along two axes: along the horizontal axis of the radiator's location and along the vertical axis (Figure 6(b)).
3. Movement of radiators along three axes (Figure 6(c)).

Using the previously derived  $|c_i| \rightarrow \min$  recommendation for  $(\Delta x_n; \Delta y_n; \Delta z_n) \leq \lambda$ , we optimized radiator locations and compared the results.

Table 1 lists the antenna coordinates obtained after optimization using three optimization options.

Table 2 presents the  $|c_i|$  module for the cases before and after optimization.

Table 3 shows the electric-field strength amplitudes at the receiving point before and after optimization.

From the viewpoint of a wireless communication link, an increase in the electric-field level at the receiving position corresponds to an increase in the useful received signal level when the receiving antenna and other link conditions remain unchanged. Therefore, the field enhancement obtained after coordinate optimization may provide additional link margin and may improve the signal-to-noise ratio if noise and interference conditions are unchanged. The present work does not attempt to predict a specific data rate, since such a prediction would require additional information about receiver noise, interference, bandwidth, modulation, and coding. The electric-field level is therefore used here as the electromagnetic performance indicator directly addressed by the proposed method.

Table 4 shows signal amplitudes and phases calculated for the required antenna configuration and reception point before and after optimization.

For a fair comparison of electric-field distributions, the excitations used for all considered antenna configurations were normalized to the same total transmitted power. Thus, although the amplitudes and phases of the individual excitation signals differ between the initial and optimized configurations, the total transmitted power remains unchanged. Consequently, the increase in the electric-field amplitude at the prescribed receiving point after optimization is associated with redistributing the

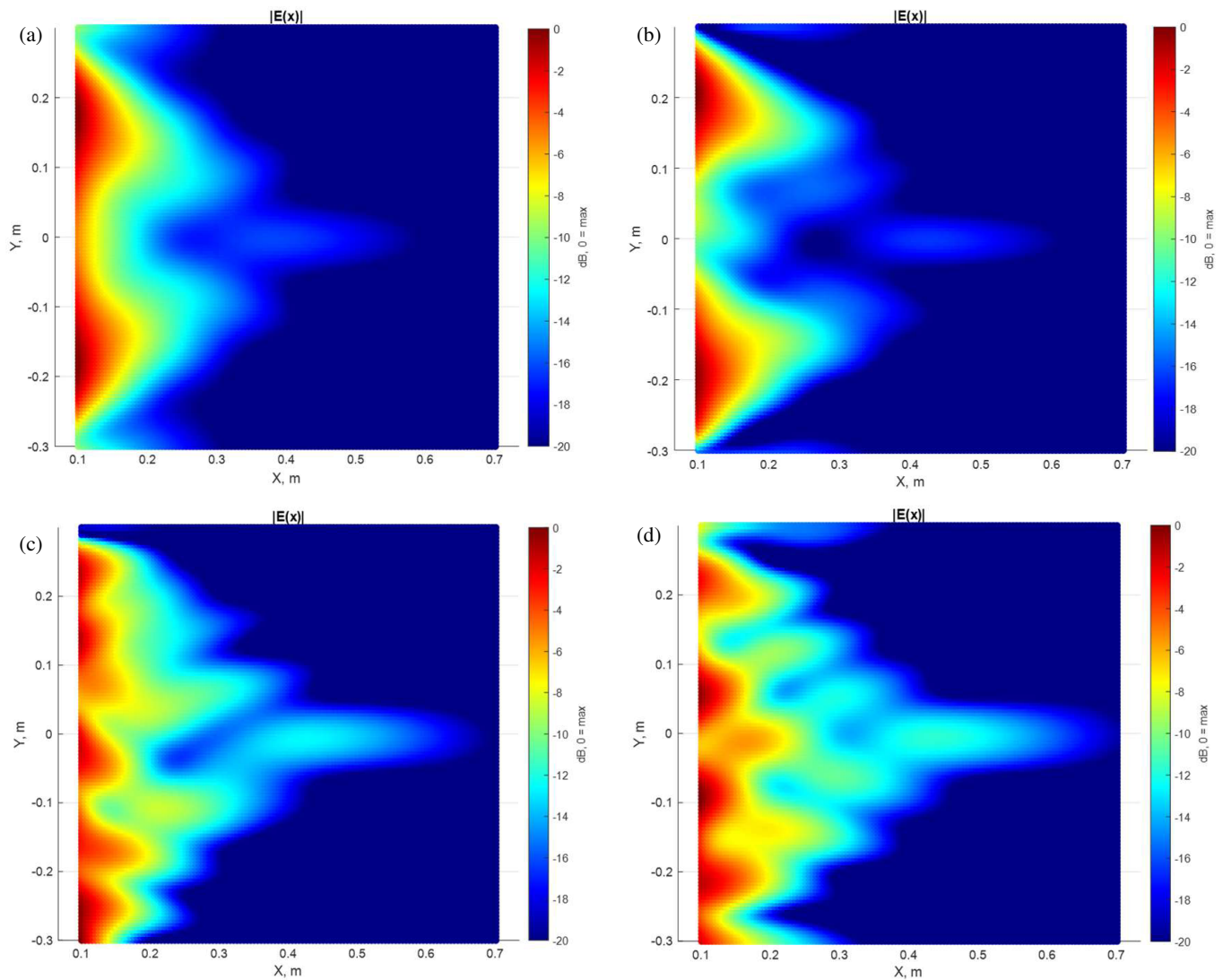


**FIGURE 7.** Electromagnetic simulation of the two-dimensional electric-field distribution in CST Studio Suite: (a) before optimization taking into account the mutual interaction of the radiators, (b) after one-axis optimization, (c) after two-axis optimization, and (d) after three-axis optimization.

excitation among array elements and changing their spatial configuration, rather than increasing the total transmitted power.

Figure 7 shows the dependence of the amplitudes of the electric field before and after optimization. Because the problem is formulated in terms of electromagnetic field formation at a prescribed position, the field distribution in the observation plane is more informative for this analysis than a conventional one-dimensional angular radiation-pattern cut. Therefore, Figure 7 presents a two-dimensional spatial distribution of the electric-field magnitude before and after optimization. This representation makes it possible to assess not only the field value at the receiving point but also the spatial localization and deformation of the high-field region caused by the mutual interaction of the radiators and subsequent variation of their coordinates.

To verify obtained results by an independent electromagnetic approach, additional full-wave simulations were performed in Computer Simulation Technology (CST) Studio Suite. The antenna configurations obtained before and after coordinate optimization were reproduced in the electromagnetic simulator,

and the corresponding electric-field distributions were calculated. Full-wave simulations confirmed the same tendency as the proposed mathematical model: varying the radiator coordinates modifies the spatial-field distribution and leads to an increased electric-field amplitude at the prescribed receiving point for optimized configurations. Thus, the CST results provide an electromagnetic validation of the numerical results obtained using the proposed optimization procedure.

Figure 8 shows the dependence of the value of  $|c_i|$  on the radiator number for the cases before and after optimization.

Analyzing the obtained results, it can be noted that the magnitude of the mutual influence of the radiators  $|c_i|$  decreases, and the more axes of coordinate change during optimization, the smaller the value of  $|c_i|$  is. It is also worth noting that at each stage of optimization, the amplitude of the electric field at the receiving point increased and took the greatest value during optimization along three axes.

The one-, two-, and three-axis optimization cases can also be interpreted as an assessment of the influence of positional

**TABLE 1.** Coordinates of radiators.

| No. | Before optimization |         |      | Single-axis optimization |         |      | Two-axis optimization |         |      | Three-axis optimization |         |         |
|-----|---------------------|---------|------|--------------------------|---------|------|-----------------------|---------|------|-------------------------|---------|---------|
|     | X, m                | Y, m    | Z, m | X, m                     | Y, m    | Z, m | X, m                  | Y, m    | Z, m | X, m                    | Y, m    | Z, m    |
| 1   | 0                   | -0.4200 | 0    | 0                        | -0.4800 | 0    | -0.0299               | -0.4800 | 0    | -0.0294                 | -0.4800 | -0.0297 |
| 2   | 0                   | -0.3600 | 0    | 0                        | -0.4188 | 0    | 0.0299                | -0.4659 | 0    | 0.0158                  | -0.4800 | 0.0289  |
| 3   | 0                   | -0.3000 | 0    | 0                        | -0.3548 | 0    | 0.0266                | -0.3700 | 0    | 0.0214                  | -0.3771 | 0.0290  |
| 4   | 0                   | -0.2400 | 0    | 0                        | -0.2889 | 0    | 0.0133                | -0.2984 | 0    | -0.0291                 | -0.3028 | 0.0297  |
| 5   | 0                   | -0.1800 | 0    | 0                        | -0.2214 | 0    | -0.0220               | -0.2307 | 0    | -0.0288                 | -0.2287 | -0.0011 |
| 6   | 0                   | -0.1200 | 0    | 0                        | -0.1511 | 0    | -0.0284               | -0.1576 | 0    | -0.0246                 | -0.1553 | -0.0291 |
| 7   | 0                   | -0.0600 | 0    | 0                        | -0.0819 | 0    | -0.0278               | -0.0821 | 0    | -0.0287                 | -0.0789 | 0.0293  |
| 8   | 0                   | 0       | 0    | 0                        | -0.0126 | 0    | -0.0278               | -0.0056 | 0    | -0.0289                 | -0.0019 | -0.0291 |
| 9   | 0                   | 0.0600  | 0    | 0                        | 0.0755  | 0    | -0.0284               | 0.0705  | 0    | -0.0294                 | 0.0794  | -0.0289 |
| 10  | 0                   | 0.1200  | 0    | 0                        | 0.1476  | 0    | -0.0287               | 0.1469  | 0    | -0.0289                 | 0.1575  | 0.0292  |
| 11  | 0                   | 0.1800  | 0    | 0                        | 0.2183  | 0    | -0.0038               | 0.2207  | 0    | -0.0298                 | 0.2302  | -0.0282 |
| 12  | 0                   | 0.2400  | 0    | 0                        | 0.2872  | 0    | -0.0292               | 0.2934  | 0    | -0.0292                 | 0.3065  | 0.0293  |
| 13  | 0                   | 0.3000  | 0    | 0                        | 0.3540  | 0    | -0.0291               | 0.3660  | 0    | -0.0297                 | 0.3826  | 0.0298  |
| 14  | 0                   | 0.3600  | 0    | 0                        | 0.4185  | 0    | -0.0290               | 0.4484  | 0    | -0.0277                 | 0.4799  | 0.0275  |
| 15  | 0                   | 0.4200  | 0    | 0                        | 0.4800  | 0    | 0.0242                | 0.4800  | 0    | 0.0250                  | 0.4800  | -0.0299 |

**TABLE 2.** Modulus  $|c_i|$  values.

| No. | Before optimization, V/m | Single-axis optimization, V/m | Two-axis optimization, V/m | Three-axis optimization, V/m |
|-----|--------------------------|-------------------------------|----------------------------|------------------------------|
| 1   | 0.0108                   | 0.0177                        | 0.00001                    | 0.0001                       |
| 2   | 0.0163                   | 0.0077                        | 0.0061                     | 0.0035                       |
| 3   | 0.0217                   | 0.0196                        | 0.0075                     | 0.0025                       |
| 4   | 0.0248                   | 0.0140                        | 0.0057                     | 0.0007                       |
| 5   | 0.0318                   | 0.0159                        | 0.0056                     | 0.0039                       |
| 6   | 0.0282                   | 0.0174                        | 0.0005                     | 0.0047                       |
| 7   | 0.0244                   | 0.0104                        | 0.0110                     | 0.0045                       |
| 8   | 0.0212                   | 0.0060                        | 0.0046                     | 0.0043                       |
| 9   | 0.0244                   | 0.0067                        | 0.0056                     | 0.0012                       |
| 10  | 0.0282                   | 0.0117                        | 0.0014                     | 0.0028                       |
| 11  | 0.0318                   | 0.0171                        | 0.0027                     | 0.00001                      |
| 12  | 0.0248                   | 0.0125                        | 0.0000                     | 0.0056                       |
| 13  | 0.0217                   | 0.0197                        | 0.0051                     | 0.0011                       |
| 14  | 0.0163                   | 0.0070                        | 0.0057                     | 0.0032                       |
| 15  | 0.0108                   | 0.0176                        | 0.0094                     | 0.0052                       |

**TABLE 3.** Amplitude of electric field strength at the receiving point.

| Reception point number | Before optimization, dB | Single-axis optimization, dB | Two-axis optimization, dB | Three-axis optimization, dB |
|------------------------|-------------------------|------------------------------|---------------------------|-----------------------------|
| 16                     | -17.73                  | -17.25                       | -13.44                    | -12.35                      |

restrictions on the achievable result. Restriction of the radiator motion to one coordinate provides the smallest spatial freedom for the optimizer. Allowing changes along two, then three coordinates progressively enlarges the set of admissible antenna configurations.

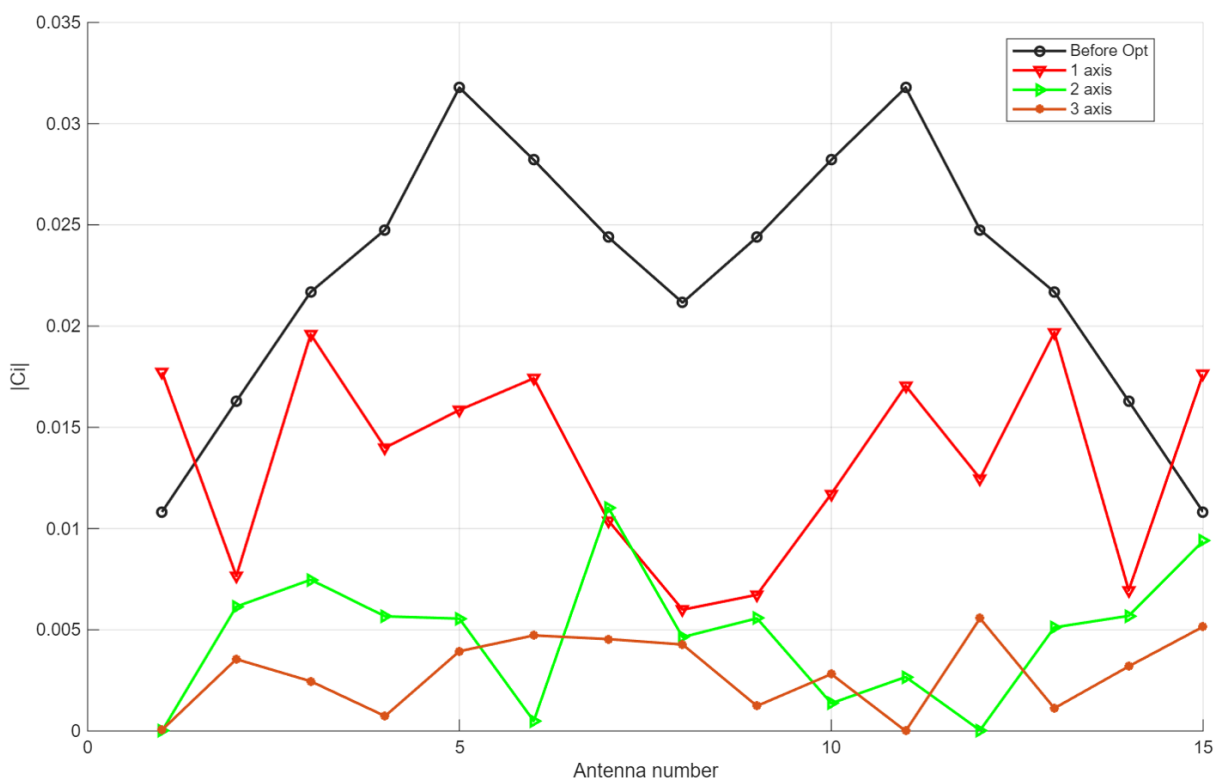
The obtained results show that increasing available spatial freedom is accompanied by reducing the mutual interaction between radiators and increasing the electric-field level at the receiving point. At the same time, restriction to fewer displacement directions preserves a more constrained antenna geometry.

Thus, the considered cases demonstrate the practical trade-off between geometrical restrictions imposed on radiator placement and the electromagnetic performance achievable after optimization.

Thus, within the adopted electromagnetic model, the influence of the mutual-coupling matrix  $|S_{TT}|$  on the calculated signal amplitudes and phases is numerically demonstrated, which in turn results in modifying the spatial electric-field distribution.

TABLE 4. Signal amplitudes and phases.

| No. | Amplitudes and phases before optimization |            | Single-axis optimization |            | Two-axis optimization |            | Three-axis optimization |            |
|-----|-------------------------------------------|------------|--------------------------|------------|-----------------------|------------|-------------------------|------------|
|     | Amplitude, V                              | Phase, deg | Amplitude, V             | Phase, deg | Amplitude, V          | Phase, deg | Amplitude, V            | Phase, deg |
| 1   | 0.0455                                    | -169.3352  | 0.0285                   | 130.8721   | 0.0196                | 15.1326    | 0.0197                  | 14.1015    |
| 2   | 0.0386                                    | -149.3305  | 0.0685                   | -176.1572  | 0.0489                | 164.8785   | 0.0396                  | 126.8566   |
| 3   | 0.0338                                    | 137.6429   | 0.0176                   | -151.6302  | 0.0249                | 15.1312    | 0.0336                  | 0.4683     |
| 4   | 0.0738                                    | 162.2394   | 0.0460                   | 123.1622   | 0.0325                | 87.1662    | 0.0244                  | -33.6919   |
| 5   | 0.0783                                    | -168.6682  | 0.0683                   | 158.2186   | 0.0256                | 87.6570    | 0.0425                  | 84.6082    |
| 6   | 0.0659                                    | -145.9114  | 0.0538                   | -163.8300  | 0.0634                | 161.1098   | 0.0488                  | 140.6844   |
| 7   | 0.0492                                    | -130.8441  | 0.0380                   | -139.0664  | 0.0369                | -159.7314  | 0.0315                  | -175.0448  |
| 8   | 0.0434                                    | -127.0803  | 0.0177                   | -83.5890   | 0.0399                | -172.8505  | 0.0401                  | -172.3396  |
| 9   | 0.0492                                    | -130.8441  | 0.0210                   | -110.0637  | 0.0417                | -143.8439  | 0.0370                  | -163.0770  |
| 10  | 0.0659                                    | -145.9114  | 0.0535                   | -165.1730  | 0.0668                | 143.9677   | 0.0427                  | 115.6967   |
| 11  | 0.0783                                    | -168.6682  | 0.0661                   | 159.7428   | 0.0292                | 65.7947    | 0.0299                  | 64.8360    |
| 12  | 0.0738                                    | 162.2394   | 0.0485                   | 120.7786   | 0.0403                | 100.2254   | 0.0168                  | 28.9867    |
| 13  | 0.0338                                    | 137.6429   | 0.0161                   | -151.2609  | 0.0244                | -168.1471  | 0.0266                  | -157.9938  |
| 14  | 0.0386                                    | -149.3305  | 0.0677                   | -177.0269  | 0.0210                | 84.6065    | 0.0247                  | 35.9705    |
| 15  | 0.0455                                    | -169.3352  | 0.0283                   | 131.0252   | 0.0396                | 150.2188   | 0.0343                  | 124.7776   |

FIGURE 8. Dependence of the value of  $|C_i|$ .

## 5. CONCLUSION

Introducing a column vector containing the complex amplitudes of signals at radiation points (locations of radiating antennas) made it possible to use it as a criterion for the mutual influence of radiating antennas on each other, the so-called magnitude of the mutual influence of antennas  $|C_i|$ . This made it possible to develop an algorithm for optimizing the location of antenna radiators within a given region of space in such a way

as to ensure the minimization of the values of the column vector  $[C]$ , which serves as a criterion for the mutual influence of antennas. Optimization was carried out according to the recommendation of  $|C_i| \rightarrow \min$  for  $(\Delta x_n; \Delta y_n; \Delta z_n) \leq \lambda$ , because if this condition is not met, parasitic effects appear [5–7, 18, 19], spoiling the resulting distribution of the electric field.

The numerical results demonstrate that changing radiator coordinates within the imposed constraints can reduce the mutual-

interaction measure and modify the electric-field distribution at the prescribed receiving point.

The presented results should be regarded as a proof-of-concept demonstration of the proposed radiator-coordinate optimization approach for the considered free-space configuration. The principal subject of the study is the relationship between the mutual interaction of the radiating elements, their spatial positions, and the resulting electric-field distribution. The genetic algorithm is used as a numerical tool for solving this coordinate-search problem and is not itself the principal contribution of the work.

The numerical example intentionally uses a 15-element linear array, an isotropic element pattern, one receiving point, and a free-space propagation model to investigate the considered effect under controlled conditions. The comparison of one-, two-, and three-axis optimization demonstrates that the imposed geometrical restrictions directly affect the achievable reduction in mutual interaction and the resulting electric-field level.

## REFERENCES

- [1] Khorov, E., A. Kiryanov, and A. Krotov, "Joint power control and time division to improve spectral efficiency in dense Wi-Fi networks," in *2018 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*, 1–5, Batumi, Georgia, June 2018.
- [2] Zheng, J., Q. Ren, B. Wang, and Y. Zhang, "Performance modeling of an NR-U and WiFi coexistence system using the NR-U category-4 LBT procedure and 802.11 e EDCA mechanism in the presence of hidden nodes," *IEEE Internet of Things Journal*, Vol. 10, No. 18, 16 658–16 674, September 2023.
- [3] Iuzvik, D. and M. Stepanov, "Formation of multiple electromagnetic field minima at prescribed locations," *Progress In Electromagnetics Research C*, Vol. 168, 217–224, 2026.
- [4] Iuzvik, D. and M. Stepanov, "Focusing of the electromagnetic field in several given areas of space," *Progress In Electromagnetics Research M*, Vol. 113, 11–22, 2022.
- [5] Headrick, J. M., S. J. Anderson, and M. Skolnik, "Hf over-the-horizon radar," *Radar handbook*, 2008.
- [6] Pozar, D. M., *Microwave Engineering*, 4th ed., John Wiley & Sons, 2012.
- [7] Bhattacharyya, A. K., *Phased Array Antennas: Floquet Analysis, Synthesis, BFNs, Metamaterial, and Active Array Systems*, 2nd ed., John Wiley & Sons, 2026.
- [8] Odabasi, H., G. Turan, and M. Salimitorkamani, "Mutual coupling reduction between closely spaced patch antennas using complementary electric-field-coupled resonators," *Microwave and Optical Technology Letters*, Vol. 65, No. 9, 2656–2665, May 2023.
- [9] Ramos, A., T. Varum, and J. N. Matos, "A review on mutual coupling reduction techniques in mmwaves structures and massive MIMO arrays," *IEEE Access*, Vol. 11, 143 143–143 166, 2023.
- [10] Hui, H. T., M. E. Bialkowski, and H. S. Lui, "Mutual coupling in antenna arrays," *International Journal of Antennas and Propagation*, Vol. 2010, 1–2, 2010.
- [11] Gao, Y., S. Wang, O. Falade, X. Chen, C. Parini, and L. Cuthbert, "Mutual coupling effects on pattern diversity antennas for MIMO femtocells," *International Journal of Antennas and Propagation*, Vol. 2010, 1–8, 2010.
- [12] Kolomvakis, N. and E. Björnson, "Exploiting mutual coupling characteristics for channel estimation in holographic MIMO," in *GLOBECOM 2024 — 2024 IEEE Global Communications Conference*, 3570–3575, Cape Town, South Africa, December 2024.
- [13] Balanis, C. A., *Antenna Theory: Analysis and Design*, John Wiley & sons, 2016.
- [14] Stutzman, W. L. and G. A. Thiele, *Antenna Theory and Design*, John Wiley & Sons, 2012.
- [15] Silver, S., *Microwave Antenna Theory and Design*, IET, 1984.
- [16] Sklar, B., *Digital Communications: Fundamentals and Applications*, Pearson, 2021.
- [17] Lo, Y. T. and S. W. Lee, *Antenna Handbook: Theory, Applications, and Design*, Springer Science & Business Media, 2013.
- [18] Colton, D. L. and R. Kress, *Inverse Acoustic and Electromagnetic Scattering Theory*, Springer, 1998.
- [19] Tai, C. T., *Dyadic Green's Functions in Electromagnetic Theory*, Intext Educational Publishers, 1971.
- [20] Iuzvik, D. and M. Stepanov, "Formation of the maximum amplitude of the electric field strength using two one-dimensional linear antenna arrays located orthogonal to each other," *Journal of Electromagnetic Waves and Applications*, Vol. 38, No. 18, 2106–2123, November 2024.
- [21] Polyak, B. T., "Introduction to optimization," New York, 1987.
- [22] Boyd, S., *Convex Optimization*, Cambridge, 2004.
- [23] Fletcher, R., *Practical Methods of Optimization*, Wiley, May 2000.
- [24] Beck, A., *Introduction to Nonlinear Optimization: Theory, Algorithms, and Applications with Python and MATLAB*, Society for Industrial and Applied Mathematics, 2024.
- [25] Messac, A., *Optimization in Practice with MATLAB®: For Engineering Students and Professionals*, Cambridge University Press, March 2015.
- [26] Michalewicz, Z., *Genetic Algorithms + Data Structures = Evolution Programs*, Springer Science & Business Media, 1996.
- [27] Goldberg, D. E., *Genetic Algorithms for Search, Optimization, and Machine Learning*, Addison-Wesley, 1989.