

Optimization of a MIMO Radar Antenna System for Automotive Applications

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Abstract—Multiple-Input Multiple-Output (MIMO) radars can improve the angular resolution of automotive radar sensors. In MIMO radars, a critical design parameter is finding the optimal placement of the transmitting and receiving arrays. Indeed, the physical position of the transceivers affects directly the properties of the virtual array. Unfortunately, the inverse mapping from the virtual array to the real transmitter-receiver configuration is still analytically unsolved. In this paper, a genetic algorithm is employed to search the optimal antenna placement. The fitness function exploits the characteristics of the ambiguity function and this allows potentially to control the ambiguity-free region of the antenna system. Numerical and experimental results confirm the suitability of this design procedure.

Index Terms—MIMO radar, antenna arrays, millimeter-wave antennas, automotive applications.

I. INTRODUCTION

Millimeter-wave radar sensors are fundamental components of driver assistance systems [1]. Adaptive Cruise Control (ACC) or emergency braking systems have been already successfully implemented in the last decade exploiting the features of radar sensors. Compared to other sensing elements, radars are robust against extreme weather conditions. The operating bandwidth is in Europe from 76 GHz to 81 GHz.

A critical requirement for automotive radar sensors is the angular resolution. In a number of applications, for example the estimation of the contour and orientation of a vehicle, high resolution radar images are required [2], [3]. The Rayleigh criterion [1] relates the angular resolution with the dimension of the sensing element, i.e. with the aperture of the antenna array. Larger antenna systems allow thus to improve the angular resolution of the sensor. However, an increase in the overall dimensions of the sensor could cause a more difficult integration beyond the bumper of the car. To overcome this practical limitation, MIMO radars could be employed. A MIMO radar transmits multiple probing signals [4] that enable the synthesis of a virtual array wider than the physical one. The larger virtual aperture provides the required improved angular resolution.

The properties of the virtual array are directly affected by the physical placement of the antennas [5]. Unfortunately, the inverse mapping from the virtual array to the real transmitter-receiver configuration is analytically unsolved [6]. Many papers have discussed possible strategies for the optimal antenna placement in MIMO radars, like for instance [5] and [7]. How-

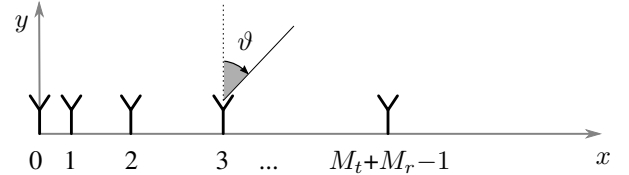


Fig. 1. Arrangement of the arrays and description of the reference system.

ever, a previous work [8] showed that the antenna positions and characteristics influence different system metrics, for example the achievable unambiguous range in the direction of arrival (DoA) estimation. Therefore, the search of the optimal antenna positions must take into account the specific application and the desired system requirements.

Indeed, the unambiguous range in the DoA estimation is a fundamental metric for the description of the performance of a radar system. In particular, it can be analyzed by plotting the ambiguity function [9], which shows the antenna system capability to distinguish between two or more signals incoming from different directions. In particular, for an automotive radar it is necessary to avoid ambiguities or near-ambiguities in the field of view of the sensor. An ambiguity would cause a wrong estimation of the DoA of the signal, which could cause in turn for example a wrong emergency braking intervention.

In this paper a genetic algorithm is employed for searching the optimal placement of the antennas. First of all, in Section II the signal model is shortly introduced. A detailed description of the algorithm and a discussion about the definition of a suitable fitness function are given in Section III. Some numerical examples and measurement results to validate the proposed approach can be found in Section IV. Finally, the conclusion in Section V summarizes the main outcomes of this work.

II. SIGNAL MODEL

The signal model that is used in this work is similar to what is presented in [8]. The system is composed of M_t transmitting and M_r receiving antenna arrays arranged on a one-dimensional lattice, as depicted in Fig. 1. Only a multistatic scenario is considered, i.e. the transmitting and the receiving antenna arrays are at different positions.

The targets are assumed to be in the far-field of the antenna array and therefore plane waves impinge on the targets and the directions of propagation of the incoming signals (the angle ϑ drawn in Fig. 1) are the same for each element of the array. Due to the specific application, in this paper the azimuth plane is of interest since only the azimuth resolution must be optimized in an automotive scenario [3].

According to the reference system, the first antenna array is placed in the origin. Let x_{Tk} and x_{Rl} describe the positions of the transmitters and receivers, respectively, with $k = 1, \dots, M_t$ and $l = 1, \dots, M_r$. Then, in the ideal case of isotropic radiators the transmitter and receiver steering vectors associated to the direction ϑ can be written as

$$\mathbf{a}(\vartheta) = \begin{bmatrix} e^{j2\pi \frac{x_{T1}}{\lambda_0} \sin(\vartheta)} \\ \vdots \\ e^{j2\pi \frac{x_{TM_t}}{\lambda_0} \sin(\vartheta)} \end{bmatrix}, \quad \mathbf{b}(\vartheta) = \begin{bmatrix} e^{j2\pi \frac{x_{R1}}{\lambda_0} \sin(\vartheta)} \\ \vdots \\ e^{j2\pi \frac{x_{RM_r}}{\lambda_0} \sin(\vartheta)} \end{bmatrix},$$

where λ_0 is the wavelength in free space.

The virtual array steering vector associated to the MIMO antenna configuration can be hence calculated as

$$\mathbf{y}(\vartheta) = \mathbf{a}(\vartheta) \otimes \mathbf{b}(\vartheta),$$

where $\otimes$ refers to the Kronecker product. The radiation pattern of the antennas can also be taken into account by multiplying the steering vector by the complex radiation pattern.

To understand the following analysis about the genetic algorithm and specifically the choice of the fitness function, it is important to define the ambiguity function (AF). According to [9], the AF of the virtual array is defined as

$$\chi(\vartheta_i, \vartheta_j) = \frac{|\mathbf{y}(\vartheta_i)^H \mathbf{y}(\vartheta_j)|}{\|\mathbf{y}(\vartheta_i)\| \|\mathbf{y}(\vartheta_j)\|}, \quad (1)$$

where the symbol $(\cdot)^H$ denotes the complex conjugate (Hermitian) vector. The AF shows the ambiguity and resolution characteristics of the virtual array. Both are fundamentally related to the geometry of the virtual array [9], which then in turn depends on the placement of the real transmitting and receiving antennas. The magnitude of the AF is always between 0 and 1, where 0 represents an orthogonal response and 1 represents identical response of the antennas at the two angles.

For the sake of completeness, the transmit-receive beam pattern (BP) of the virtual array for a specific DoA ϑ_0 can also be defined. According to [10], it is given by

$$\text{BP}(\vartheta, \vartheta_0) = \frac{|\mathbf{y}(\vartheta)^H \mathbf{y}(\vartheta_0)|^2}{\|\mathbf{y}(\vartheta)\|^2}. \quad (2)$$

III. OPTIMIZATION OF THE ANTENNA PLACEMENT

A. Genetic Algorithm

A genetic algorithm is employed for finding the optimal antenna placement [11]. Genetic algorithms belong to the class of evolutionary algorithms and their use for solving electromagnetic problems is well-established since their introduction.

In this work, the classical skeleton of a genetic algorithm is retained and it calculates the best position for the antennas. The algorithm can be used for both monostatic or multistatic configurations, although in this paper only the multistatic case will be discussed.

The algorithm starts with determining the virtual array length using the Rayleigh criterion for a desired angular resolution $\Delta\varphi$ as [1]

$$\Delta\varphi = 1.22 \frac{\lambda_0}{d_v},$$

where d_v is the maximal virtual array aperture. Actually, the angular resolution of the radar sensor is a system specification that does not only depend on the antenna placement, but also for example on the following signal processing.

It is assumed that the first transmitter is placed in the origin, at the position $x_{T1}=0$. Therefore, the M_t+M_r-1 remaining positions have to be found. The minimum distance between two adjacent antennas can be specified and it is called $d_{\min}$. For a multistatic configuration, the sum of the positions of the last transmitter $x_{TM_t}=\max(\mathbf{x}_t)$ and the position of the last receiver $x_{RM_r}=\max(\mathbf{x}_r)$ must be equal to d_v .

In this example it is assumed that the first positions will be occupied by the transmitters and the following by the receivers; it is however possible to consider different configurations, too.

The genes are the elementary units of the genetic algorithm [11]. In this case, they describe the position of a transmitting or receiving antenna. The number of bits required for representing a gene depends on the virtual aperture d_v .

A chromosome is then defined as a set of genes that denotes the position of the antenna elements. In the first iteration, a random population of chromosomes is generated. This is done by first calculating the random positions of M_t-1 transmitters starting from the position $d_{\min}$, since the first transmitter is considered to be at $x=0$. Then the random positions for M_r receivers are determined within $\max(\mathbf{x}_t)+d_{\min}$ and $d_v-\max(\mathbf{x}_t)$, where $\mathbf{x}_t$ is the vector that contains the position of the transmitters. Moreover, to have sufficient place to accommodate the remaining receivers the following condition must be satisfied:

$$d_v - 2 \max(\mathbf{x}_t) \geq (M_r - 1) d_{\min}.$$

The above constraints are a general approach for the placement of transmitters and receivers. However, they can also be amended to suite better the application or to include further hardware requirements.

In the next step, the fitness function f_n must be evaluated for each of the chromosomes in the population. In the next subsection, a more detailed description of the fitness functions will be given. The chromosomes are then sorted based on their fitness values and the lower half or some chosen percentage of the population is discarded. The discarded amount of population is regenerated using crossover and then with mutation. Once crossover and mutation are done, the constraints are checked if the newly generated transmitter and receiver

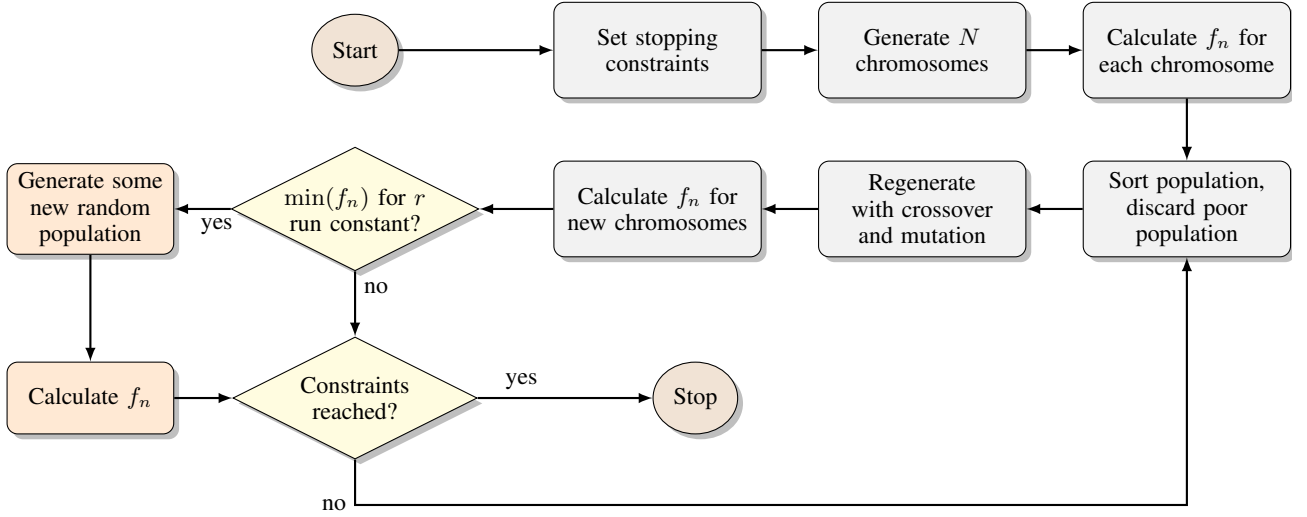


Fig. 2. Flow chart of the genetic algorithm for the placement of the antennas.

positions are within their respective range. The fitness of the newly generated chromosomes is calculated and appended into the fitness matrix. If the algorithm has the same minimum fitness value for say r continuous iterations, then a certain percentage of the population is discarded and is replaced with new randomly generated population. This helps the algorithm to come out of a local minimum, and hence false convergence. The value r is crucial, as a smaller value will increase the number of computations and a larger value could not prevent the local minima as the maximum number of iterations will be reached. This process is repeated until the maximum number of runs is reached.

Since the initial random population and the number of iterations are key parameters for the convergence of the genetic algorithm, a general criterion is to have a population of 10 times the number of genes in a chromosome [11] and number of iterations equal at least to 20. For the examples described in this paper, the number of iterations is equal to 20.

The flow chart in Fig. 2 illustrates the main steps of the used genetic algorithm.

B. Selection of the Fitness Function

The aforementioned outline of the proposed genetic algorithm is similar to what is already widely employed for many electromagnetic problems. More interesting and intimately related to the specific application is the search of a suitable fitness function.

The fitness function must be a measure of system performance to be maximized or minimized [12]. In the previous section two important metrics have been mentioned, in particular the AF in (1) and the BP of the virtual array in (2). Both functions could be used for the definition of a proper fitness function.

As first choice, the fitness function is calculated on the sidelobe level (SLL) of the BP. A desired fixed value of SLL can be given and then the fitness is calculated by counting

the highest SLL in a certain angular range. More specifically, the angular range is defined in this example between the main beam and $\pm 45^\circ$, which is sufficiently wide for automotive applications. In this range the algorithm tries to suppress the SLL, similarly to what is usually done in array synthesis problems. However, it is important to recall that the BP in (2) is defined for a specific DoA ϑ_0 , hence the required SLL is specified for a fixed DoA, too.

The second option is to relate the fitness function with the AF. From the plot of the AF it is possible to identify the ambiguity-free region, i.e. the angular range in which it is possible to estimate unambiguously the DoA of the incoming signal. In this case, first a threshold on acceptable values of the AF must be given, which can be any value between 0 and 1 according to the application requirements; then the algorithm maximizes the size of the ambiguity-free region. In particular, the size of the ambiguity-free region is calculated from the plot of the AF by counting the number of contiguous points where the ambiguity function has a value lower than the threshold, starting from the center of the main diagonal and taking into account also the desired angular resolution. As an example, the square of Fig. 6 represents the ambiguity-free region evaluated from the plot of the AF. The algorithm aims at maximizing the area of the square to minimize the fitness function.

The second method for the definition of the fitness function has an inherent advantage compared to the previous method based on the BP. If based on the AF, the fitness function is independent from a specific DoA and the optimization process is hence more general. Actually, such an optimization based on the properties of the AF allows to take all the possible DoA of interest at the same time into account. The method based on the BP minimizes the SLL only for a specific DoA and it is not possible to control the BP for different directions in this implementation of the algorithm. On the other hand, the computation of the fitness function based on the BP is significantly faster. The result of the optimization process can

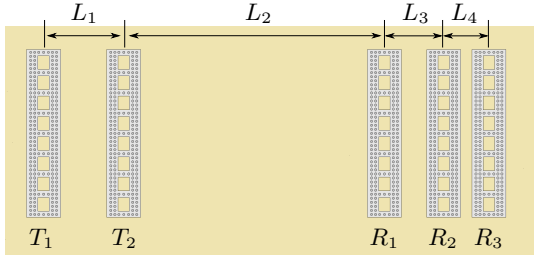


Fig. 3. Schematic of the antenna system for the MIMO radar configuration. The distances between the antenna arrays are (in mm): $L_1=9.9$, $L_2=32.2$, $L_3=7.3$, $L_4=5.6$. T_i and R_j describe the transmitters and receivers, respectively.

be quickly calculated, compared to the longer computation time required by the method based on the AF when a large number of iterations is necessary. The optimization based on the AF in fact involves matrices operations which are complex and time consuming.

IV. EXAMPLES AND DISCUSSION

To show the validity of the proposed approach, numerical and experimental examples will be given.

In particular, an antenna system potentially suited for an automotive radar application has been designed. By considering the examples reported in [13] and the typical dimensions of a commercial automotive radar sensor, an antenna system composed of five elements, two transmitters and three receivers has been designed. Using the genetic algorithm with the fitness function based on the AF method, the final positions for the antennas have been found and they are equal to

$$\mathbf{x}_t = [0, 2.54\lambda_0], \mathbf{x}_r = [10.81\lambda_0, 12.69\lambda_0, 14.13\lambda_0],$$

where $\mathbf{x}_t$ and $\mathbf{x}_r$ are the vectors containing the positions of the transmitting and receiving arrays in terms of free-space wavelength at 77 GHz. This arrangement of the arrays sets a virtual aperture of $d_v=16.67\lambda_0$, corresponding to a nominal value of the angular resolution of 4.2° . A schematic of the antenna configuration is depicted in Fig. 3.

As can be seen from Fig. 3 and also from the fabricated prototype shown in Fig. 4, the radiating elements are 8-element cavity antenna arrays based on the design presented in [14]. However, unlike the design described in [14], in this case a series feeding is employed. To take into account the physical dimension of the arrays and to avoid overlapping of the columns, as an additional constraint in the algorithm the minimum distance between the antenna arrays $d_{\min}$ has been set to $1.17\lambda_0$ at 77 GHz.

For the experimental evaluation of the AF depicted in Fig. 6, the two-way radiation pattern for every transmitter-receiver pair has been measured in an anechoic chamber and the results are plotted in Fig. 5. A detailed description of the measurement setup and procedure can be found in [8] and it is here omitted to avoid duplications.

As can be seen from the picture, some spots with a high value of correlation are visible; they are due to the ripples

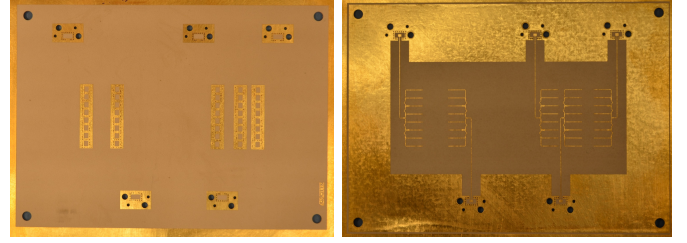


Fig. 4. Fabricated prototype: (a) front view and (b) back view. The total dimensions of the board are $9.9 \text{ cm} \times 7.1 \text{ cm}$. The PCB is a two-layer structure based on the substrate RO3003 from Rogers Corporation.

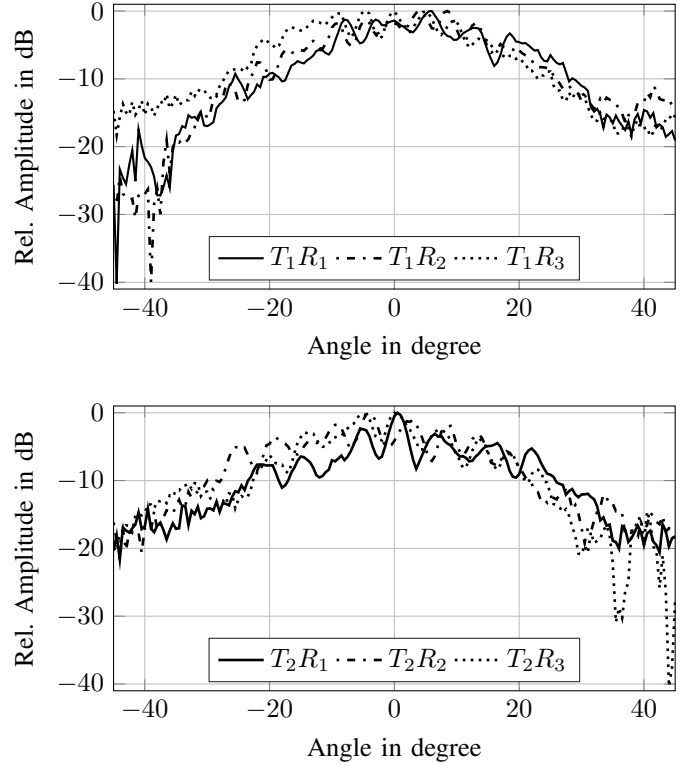


Fig. 5. Measured two-way radiation pattern at 77 GHz using (top) the transmitter T_1 and (bottom) T_2 .

measured in the two-way pattern. The surface wave excitation is indeed strong for a cavity antenna [14] and for this reason the radiation pattern is not perfectly smooth. By considering a threshold of 0.6, the ambiguity-free region is confined within $\pm 15^\circ$. As a comparison, the AF for the ideal case of isotropic radiators is depicted in Fig. 7. Obviously, in the ideal case there are no high-correlation spots out of the diagonal, but as can be seen from the larger width of the main diagonal, the angular resolution is worse than in any practical case.

In this work, the measurement results have just been compared to the ideal case of the antennas modeled by the isotropic radiators. For the sake of clarity, it is important to underline that this comparison is fair and correct. Although full-wave simulations of the arrays have been carried out, these

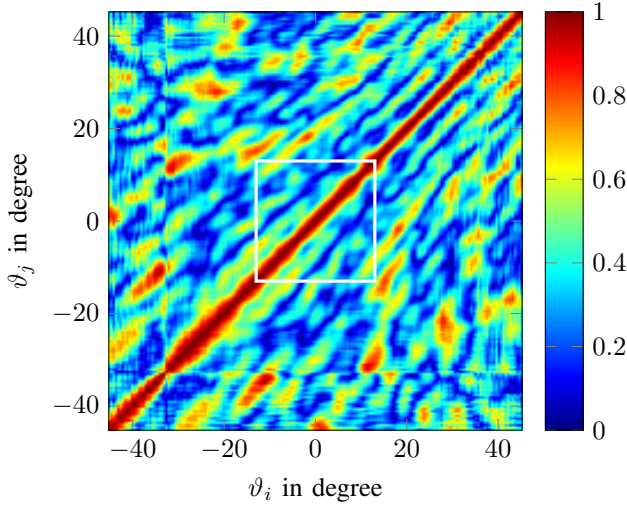


Fig. 6. AF according to (1) generated by using the measured two-way patterns at 77 GHz. The white rectangle indicates the ambiguity-free region.

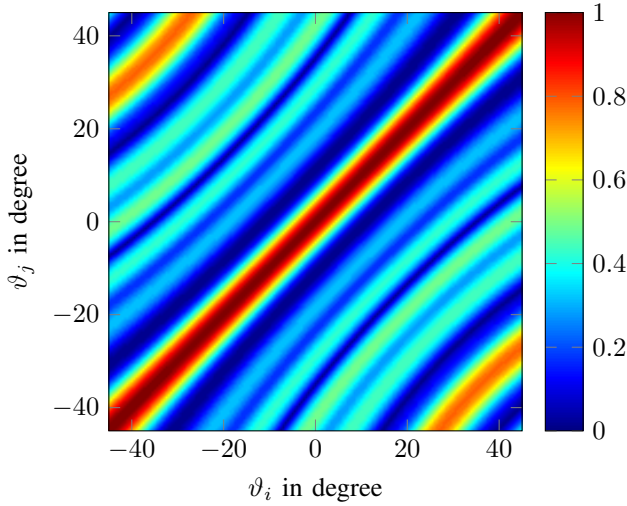


Fig. 7. AF according to (1) for the case of isotropic radiators at 77 GHz.

numerical results are not helpful for the calculation of the AF. Since it is not possible to represent in the full-wave simulator the complete antenna system reported in Fig. 3 due to the complexity of the model, only one transmitter-receiver pair has been simulated; then it has been assumed that these results are valid for all the pairs. Considering that in [8] it has been proved that when identical antennas are employed, the properties of the AF depends only on the geometrical displacement of the arrays and not on their radiation pattern, it is unnecessary to use the full-wave simulation results for the calculation of the AF, since the same results as the isotropic case are expected.

V. CONCLUSION

In this paper, a description of the design procedure of an antenna system for MIMO radar applications has been given. In particular, the optimal antenna locations have been found

by means of a genetic algorithm. The classical skeleton of a genetic algorithm has been retained, however a specific emphasis has been put on the selection of a suitable fitness function. Since the fitness function must always be related to the individual application and optimization problem, two different fitness functions based on different system metrics have been analyzed. The best one exploits the properties of the AF and allows to take into account the ambiguity-free region, which is often a main parameter for radar applications and DoA estimation problems.

Finally, as an example an antenna system with two transmitters and three receivers suitable for an automotive application has been described. Numerical and experimental results support the effectiveness of the proposed design procedure.

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