Antenna Array Geometry Optimization for a Passive Coherent Localisation System

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Abstract. Passive Coherent Localisation (PCL), also known as Passive Radar, making use of RF sources of opportunity such as Radio or TV Broadcasting Stations, Cellular Phone Network Base Stations, etc. is an advancing technology for covert operation because no active radar transmitter is required. It is also an attractive addition to existing active radar stations because it has the potential to discover low-flying and low-observable targets. The CORA (Covert Radar) experimental passive radar system currently developed at Fraunhofer-FHR features a multi-channel digital radar receiver and a circular antenna array with separate elements for the VHF- and the UHF-range and is used to exploit alternatively Digital Audio (DAB) or Video Broadcasting (DVB-T) signals. For an extension of the system, a wideband antenna array is being designed for which a new discone antenna element has been developed covering the full DVB-T frequency range. The present paper describes the outline of the system and the numerical modelling and optimisation methods applied to solve the complex task of antenna array design: Electromagnetic full wave analysis is required for the parametric design of the antenna elements while combinatorial optimization methods are applied to find the best array positions and excitation coefficients for a regular omni-directional antenna performance. The different steps are combined in an iterative loop until the optimum array layout is found. Simulation and experimental results for the current system will be shown.

Keywords: Passive Radar, Passive Coherent Localisation, Discone Antenna, Antenna Array, Beamforming
PACS: 41.20.Jb Electromagnetic wave propagation; radiowave propagation

INTRODUCTION

Instead of actively transmitting radar pulses, Passive Radar, also known as Passive Coherent Localisation, uses signals from available transmitters (sources of opportunity) for radar operation. Echoes from moving objects can thus be detected as targets. The principle of bistatic radar operation is illustrated in Figure 1. From the comparison between the direct line-of-sight signal (L) from the transmitter (T) and the signal scattered from the target object, typical radar parameters such as direction, range or velocity may be derived at the receiver (R). The subject of Passive Bistatic Radar (PBR) has been comprehensively covered in different textbooks and journals, e.g. [1,2].

The widespread existence of digital wireless communication installations and digital broadcasting stations makes the application of passive radar using these stations as illuminators attractive. Passive radar systems using analogue FM radio transmitters have been designed and systems are now commercially available. Currently there is a widespread interest in developing DAB / DVB passive radar systems because digitally coded signals have an autocorrelation function practically independent of the information content. Digital waveforms have a time-invariant bandwidth, which is typically wider than FM radio waveforms. They are, therefore, capable of yielding finer range resolution. An experimental system for verifying the feasibility of passive radar in the DVB-T frequency range has been developed at Fraunhofer FHR and is currently operated for measurements and optimisation of signal processing.

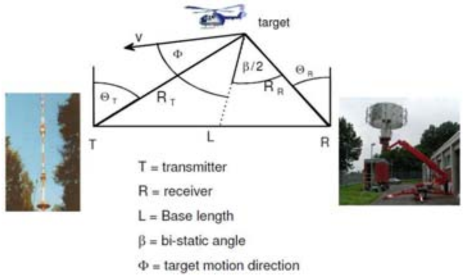

FIGURE 1. Principle of Passive Bistatic Radar

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OUTLINE OF THE CORA SYSTEM

The Covert Radar (CORA) experimental passive radar features a software defined RF-front-end consisting of 16 equal receiver channels. Each of the receiver channels comprises a low-noise amplifier (LNA), a tuneable or fixed filter and an adaptive gain control for optimum control of the Analog to Digital Converters (ADC). A/D conversion is realised with 4 FPGA boards, each processing 4 receiver channels. The 16 digital receiver channels realised in the receiver-front-end allows for 360° coverage at VHF and 180° coverage at UHF [3].

Antenna Front-End

The CORA system currently features an electronically scanned circular antenna array with separate elements for the VHF- (150-350 MHz) and the UHF-range (400-700 MHz) and is used to exploit alternatively DAB or DVB-T signals. Crossed butterfly dipoles are used for the VHF-range to enable co- and cross-polar target measurements and to adapt to the polarisation of different types of illuminators such as DAB-single-frequency networks (SFN). For the UHF-range, which hosts the DVB-T networks, flat dipoles with vertical polarisation have been realised.

DESIGN OF AN ANTENNA ARRAY FOR THE DVB-T FREQUENCY RANGE

In passive radar systems, which are to be operated with the illumination of digital Single Frequency Network (SFN) signals, e.g. DAB or DVB-T, false targets (ghosts) resulting from ambiguous transmitter-target associations can occur since all transmitters in a SFN coherently transmit the same signal at the same time. In order to reduce such ghosts target bearing measurements are important. This is typically achieved with the help of an antenna array which needs to be capable of beam-forming over the full range of 360° azimuthal coverage and, in addition, of adaptively steering radiation pattern nulls in the direction of the illuminator (i.e. the DVB transmitter). These requirements are specifically challenging in the DVB-T frequency range due to its large fractional bandwidth.

Beam-forming in a circular array requires the calibration of the elements including the influence of the antenna environment and the mutual coupling of the elements. The performance of such a calibration method, however, is largely dependent on the very location of the antenna with respect to the distribution of the transmitters. Thus, an additional antenna array for the DVB-T range is currently being developed. The structure of the new antenna will be that of an open array, which includes an additional element for antenna calibration independent of external sources.

Antenna Element Design

To adapt the frequency range of operation to the signal sources of opportunity available at the area of interest new broad band antenna elements are required. The antenna elements should be able to cover the specified frequency range of operation (450 to 900 MHz), vertically polarised and have a low weight. The discone antenna is an ideal candidate because it features large bandwidth, omnidirectional coverage, low cost and is easy to fabricate. It is a variation of a biconical antenna where one of the cones is replaced by a circular disc serving as a reflector. It may also be seen as a conical monopole antenna over a finite groundplane.

The discone antenna element for the present application has been designed in the frequency range of operation according the requirements of the CORA system using full-wave electromagnetic numerical analysis software. The antenna parameters offering the optimum performance for the present application have been found using parametric optimisation of the input reflection coefficient and bandwidth. In each iteration of the design loop, a full-wave calculation using the CST Transient Solver based on the Finite Integration Technique (FIT) [4] was conducted until sufficient performance was achieved. The antenna element has a height of 231 mm, an outer cone diameter of 194 mm, and a disc radius of 150 mm. Two antenna prototypes with different feeding sections were built and measured inside an anechoic chamber. Both antennas are fed via an SMA coaxial connector, Type A from the bottom (disc) side, the other one, Type B, from the top (cone) side, see Figure 2. They offer comparable

FIGURE 2. Prototype B of the discone antenna element with feeding from the top (cone) side.

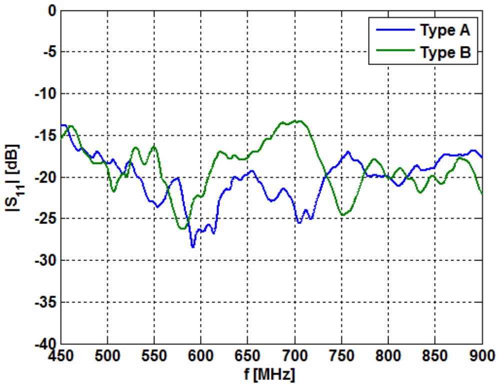

FIGURE 3. Measured Antenna Input Reflection Coefficient for antenna element type A (top fed) and B (bottom fed).

RF performance with an input reflection coefficient below -13 dB over the full frequency range at a maximum gain of approx. 3 dBi at the highest frequency of 900 MHz. A comparison of the measured antenna input reflection coefficient is shown in figure 3 for antenna element type A and B. Further details of the discone antenna element design and performance are given in [5].

Array Digital Beamforming

The definition of a general antenna array and beamforming in the receive case is shown in Figure 4. In this scenario, M signals are impinging from different directions on an array consisting of N antenna elements of arbitrary type and at arbitrary positions. Let

$$\vec{E}_m(t) = g_m(t) \cdot \vec{P}_m \cdot e^{j(\omega t - \vec{k}_m \cdot \vec{x})}$$
$$\vec{k}_m = \frac{\omega}{c_0} \begin{pmatrix} \sin\vartheta_m \cdot \cos\varphi_m \\ \sin\vartheta_m \cdot \sin\varphi_m \\ \cos\vartheta_m \end{pmatrix} \tag{1}$$

be the three-dimensional representation of a plane wave at an angular frequency of ω, which is polarised along the axis P and modulated by a narrow-band carrier signal with the complex envelope $g_m(t)$. The wave is travelling into the direction of the wave number vector k_m where c_0 is the speed of light in free space.

The signals E_m may be both signals of interest as well as unwanted signals such as interference or active jammers. The complex voltages u_i received at the ports of each antenna element and their variation over time are

$$u_i(t) = \sum_m \vec{E}_m(t) \vec{C}_i(\vartheta_m, \varphi_m) \tag{2}$$

where C_i is the characteristic radiation pattern of the i-th antenna element into the direction of arrival of the m-th incoming signal (ϑ_m, φ_m). The vector notation of E and C takes into account the polarisation of the antenna elements and of the incoming electromagnetic waves, respectively.

In the typical array processing, the contribution from each individual antenna element is multiplied by a complex weight a_i before all contributions are added to the common output.

The array sum signal s may be written as

$$s(t) = \sum_i a_i \cdot u_i(t) = \vec{a} \cdot \vec{u}$$
$$\vec{u} = (u_1, u_2, \cdots, u_N)^T \tag{3}$$
$$\vec{a} = (a_1, a_2, \cdots, a_N)^T$$

The radiation pattern of the antenna array is included in the sum signal s. It is worthwhile to note that it depends not only on time but also on the direction of incoming signals since the weighted contributions from each element may add up differently for different aspect angles. According to the theorem of reciprocity, the radiation properties are valid not only in the receive case but also for a transmitting array antennas.

It is the aim of beamforming to determine a set of excitation coefficients a_i such that the array radiation pattern takes the desired shape, e.g. the output is

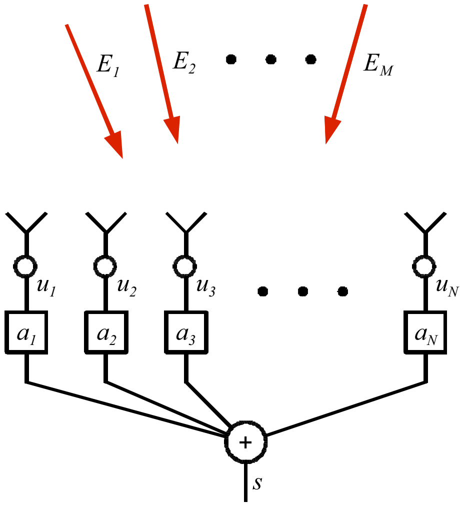

FIGURE 4. General antenna array and beamforming definition with M incoming signals and N antenna elements.

maximised for the direction of desired signals and unwanted signals in other directions are suppressed. Typically, some constraints such as a maximum beamwidth or low side lobe levels (SLL) have to be taken into account and a large number of beamforming methods for various applications and of different numerical complexity may be found in literature [6]. In the present case, a projection method has been applied in which pattern synthesis problems are solved as an intersection finding problem [7].

In addition to this deterministic beamforming approach, where array excitation coefficients are determined for a pre-defined radiation pattern also adaptive methods are required. Adaptive algorithms have traditionally been applied to time domain filtering in which the weights of filters are adapted to minimize an error based on some criteria. For an antenna array, these techniques take into account the signals u_i received at the antenna ports and the adaptation is applied to the complex weight vector a with one weight per element. Adaptive beamforming can, for instance, be used to separate users occupying the same frequency band of wireless communication systems. In the present case, it is required to supress the relatively strong direct signal from the broadcasting station and adaptively steer a minimum (null) of the radiation pattern into this direction.

At a given time t, the covariance matrix $\mathbf{R}$ may be constructed from one snapshot of received signals u and adaptive weights with maximum signal-to-interference ratio (SIR) may be calculated according to

$$\begin{aligned} \vec{a}_{\text{adapt}}(t) &= (\mathbf{I}+\mathbf{R})^{-1} \cdot \vec{a}_0 \\ \mathbf{R}(t) &= \vec{u}^* \cdot \vec{u}^T \end{aligned} \tag{4}$$

where a_0 is a pre-defined set of deterministic array weights and $\mathbf{I}$ is the identity matrix [8].

For practical applications of beamforming, the calibration of the elements including the influence of the antenna environment, the mutual coupling of the elements, and variations between different channels of the RF front-end is required. For the current antenna a calibration method [3] had been developed, which is based on the exploitation of the signals of the SFN transmitters used for illumination.

Array Geometry Optimization

To find the best possible alignment of the antenna elements, the spatial distribution of the array was investigated using parametric optimization. Since full-wave electromagnetic simulations are relatively time consuming, especially when the whole antenna array consisting of up to 16 elements is considered, approximate modelling methods using isotropic radiators or electrically short linear dipole antennas were applied. When used in combination with a Method of Moment (MoM) electromagnetic solver, the latter approach includes the effects of mutual coupling between the elements and allows for a rapid calculation but the obtained results for antenna input impedance and the embedded element radiation patterns are not fully comparable to those for an array of discone antennas. However, they were used to analyse the principal capability of a given array geometry with respect to the requirements described above and for the decision which array shape may be the most suited one.

To find the optimum positions of the antenna elements within a pre-defined area, a constrained global optimisation method based on Genetic Algorithms (GA) was applied [9]. The parameter set included the number of antenna elements and their displacement from the original positions, the excitation coefficients for the array were determined using the projection method described above. It is worthwhile to note that changes of the array geometry may cause These could, however, not be considered in the approximate modelling method using linear dipole as described above

As a starting point for the optimisation, the discone elements have been arranged in an open circular array configuration. Circular arrays are, in general, well suited to passive radar applications. They permit the forming of multiple surveillance beams providing close to 360° azimuth coverage. Furthermore, one beam can be designated as a reference and steered directly towards the illuminator of opportunity. In

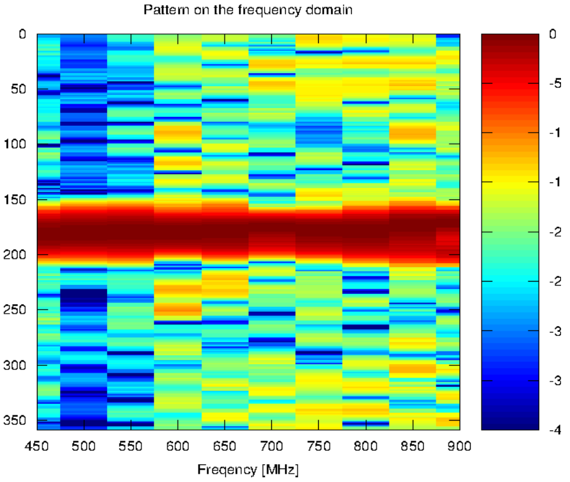

FIGURE 5. Radiation pattern simulation between 450 MHz and 900 MHz for a 13-element uniform circular array of linear dipoles.

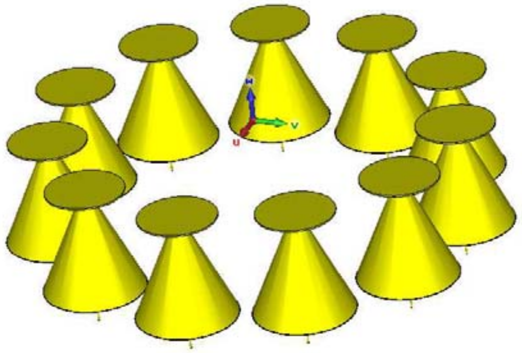

FIGURE 6. Illustration of the final configuration for the uniformly spaced circular array of consisting of 11 discone antenna elements.

addition to the obvious solution of a regular circular array, several other array configurations have been explored, e.g. two crossed linear arrays, randomly distributed elements, etc. Figure 5 shows the computation of a circular array consisting of 13 linear uniformly distributed dipole elements. The radius is 0.45 m and the main beam direction is set to an arbitrary angle of 170°. The array radiation pattern has been computed over the full frequency range between 450 MHz and 900 MHz. It can be seen that for certain frequencies the array radiation pattern begins to deteriorate: The specified gain and 3 dB beamwidth requirements cannot be met and the sidelobe level increases for certain directions. No grating lobes are present in the patterns since the inter-element spacing does not exceed 0.65 λ at the upper frequency limit.

Multiple array configurations of different basic shape have been simulated and analysed. However, none of the alternative, often more complicated, configurations have shown a significantly better performance over the full range of frequencies and aspect angles than a regularly spaced circular array [10]. With respect to hardware and system design considerations, it has finally been decided to focus on an 11-element uniform circular array. An illustration of the final configuration with the discone antenna elements equally spaced is shown in Figure 6. The diameter was fixed at 77 cm which corresponds to an inter-element spacing of 22 cm, the equivalent of a half-wavelength spacing at the centre frequency.

As an example, Figure 7 shows the normalised far-field radiation pattern of the array in the horizontal plane for a frequency of $f = 450$ MHz for Co-Polarisation (vertical) and Cross-Polarisation (horizontal). The illustration also indicates the prescribed upper and lower far-field masks used in the beamforming method which define the desired main beam position, width, and side lobe level ratio by stating maximum and minimum power levels for each direction. It may be seen that for the given width of the main beam in this example an SLL of -20 dB is achieved for the co-polarisation but the cross-polarisation rises to slightly higher levels. An isolated discone antenna element typically has a very low cross polarisation level but here an effect of the mutual coupling inside the array may be observed which affects the distribution of equivalent currents on the antenna elements and increases horizontal field components.

ANTENNA ARRAY DESIGN CYCLE

Several steps were performed in order to find an appropriate antenna array design: Decisions on the type of antenna elements and the basic array shape have been made, initial designs of isolated antennas were derived and, possibly, refined. A general overview of the design cycle that has been run through iteratively is shown in Figure 8.

Starting from the technical specification and the performance requirements for the antenna, an initial set of design parameters was produced. These parameters include the dimensions of the antenna element, the total number of elements, and their individual positions within the array. Depending on the specific task that is performed, different computational electromagnetic simulation tools are applied, i.e. full-wave methods for the analysis of the antenna array, beamforming methods for the determination of appropriate array excitation coefficients, and global optimisation methods for finding the array geometry, as described in the previous sections. It is worthwhile to note that, due to the effects of mutual coupling, a change of certain parameters can have an influence also on other

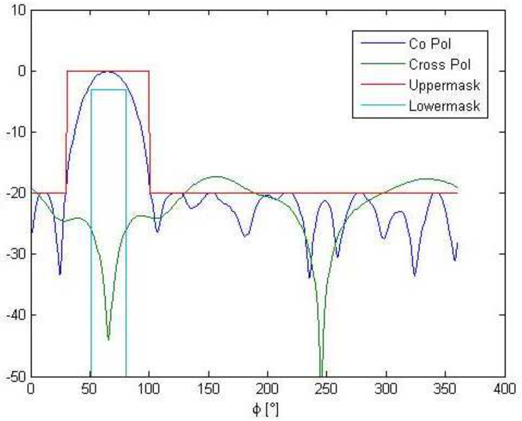

FIGURE 7. Example of a normalised far-field radiation pattern for the 11-element circular antenna array at 450 MHz.

parameters and can make the repetition of previous steps inevitable. If, for example, the geometry of the array is changed, all embedded element radiation patterns need to be re-calculated for proper analysis. Since different software packages were used for the various steps with the design loop, a significant amount of human interaction was involved for control and data format conversion.

For finding an "optimum" final set of antenna design parameters, it is essential to define a suitable COST function which evaluates the present results of the electromagnetic analysis with respect to the side constraints imposed by the system (e.g. gain, bandwidth, number of channels, etc.).

CONCLUSIONS

The outline of the CORA PCL system and the different numerical modelling and optimisation methods applied to solve the complex task of antenna array design have been presented. For the relatively small number of channels (i.e. antenna elements) available, a regularly spaced circular array has shown to be the most practical design, even if the performance may decrease for certain directions and at certain frequencies. The design parameters of an 11-element array have now been fixed and the array will be fabricated and measured shortly. Once the hardware and antenna front-end have been calibrated, the system will undergo extensive field trials.

To find an optimum antenna array geometry, different steps of an iterative design cycle have been performed. Since these steps (element design, array beamforming, investigation of topology) were performed using different software packages and several re-designs were necessary, the calculations were tedious and required a lot of manual work. For similar tasks in the future, a common design tool including the programs of the complete design loop would be helpful. However, this implies the development of new and efficient electromagnetic modelling software as well as the availability of powerful computer hardware.

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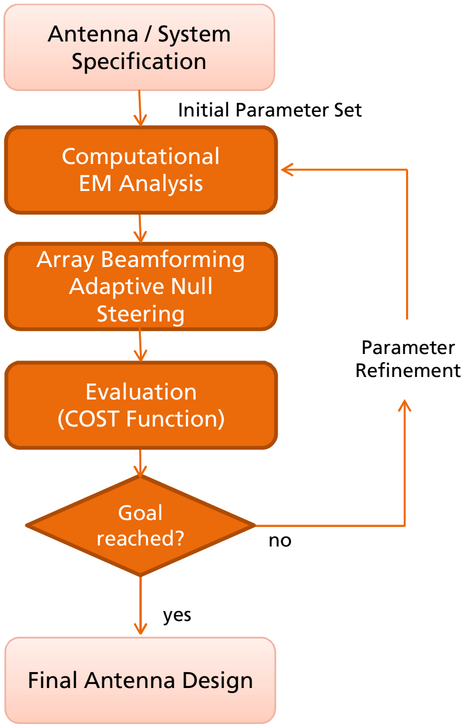

FIGURE 8. Iterative Antenna Array Design Cycle