On mutual influence of emitters in directivity optimization of shortwave phased antenna arrays

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Abstract.
The problem of short wave phased antenna arrays optimization was formulated as a quadratic programming problem. BARON solver was applied to retrieve a solution. Research of total gain dependency on frequency and density of counterweights system was performed.

1. Introduction
Phased antenna array (PAA) is an antenna system that can be presented as a regular array of emitters, each of which is connected to special devices to provide phases and magnitudes distribution in emitters to retrieve a directed radiation (see, for example, [1]). The usage of such systems is frequent for microwave range because one of the advantages of such system is relatively small size of emitters and broader wave range. However radio waves in microwave range get significantly attenuated in the atmosphere. As a consequence microwave radio systems have a short transmission distance. PAAs in shortwave range are less frequently applied because they have larger size. Nonetheless they can be used to increase transmission distance [2, 3, 4]. The possibility of increasing a radiation directivity of shortwave PAA in a given direction by choosing the proper phase and magnitude value for each emitter is researched in the current paper. The difficulty of the shortwave problem statement is the mutual influence of emitters on each other. This influence can be neutralized by using additional devices in the microwave case (see. [5], § 6.7). Without mutual influence the problem will be significantly simplified [6]. Due to a different antenna system design this simplification could not be applied in shortwave case.

In this paper we consider a problem of ring-structured PAAs directivity maximization in the given direction where the power provided for each emitter is constrained. Such problem statement can be solved with numeric methods only [7].

The paper has the following structure: the problem statement with notation is given in the section 2. In section 3 the computational experiments and their results description are provided. General conclusions are provided in the section 4.

2. The main notations and the problem statement
In this paper we research PAAs which consist of broadband vertical monopoles (BVM) (see Fig. 1). Each of the BVMs consists of 8 wires which form a “drop-like” vertical emitter. Ring-structured array of BVMs is a few “drop-like” vertical emitters which are placed in round
with some fixed step. “Web-like” counterweights system is placed in parallel to the ground on the BVMs feeding point level. Longitudinal wires of counterweight system are placed in such a way that every emitter lies on one of these wires. These wires form a sector. Transversial wires of the counterweights system connect longitudinal wires and are placed in parallel to each other in the sector. Into consideration can be taken any other PAA which is designed in some other way if the PAA optimization problem input data is provided for them. Matrix of radiation in the given direction and resistances matrix are assumed as input data. These matrices can be retrieved with some antenna modeling program.

The main purpose of the problem solution is a directivity maximization when the power which is provided for each emitter is constrained. As a quantitative measure of directivity we will denote the power density. All further presentation is based on an assumption that the field of antenna system can be presented as a superposition of partial fields of each emitter. From this point of view power density is presented in the form (1):

$$F = |i|^{\dagger} A i,$$  \hspace{1cm} (1)

where $i$ is a complex column-vector of currents, $+$ means hermitian conjugation, complex matrix $A$ has a size $N \times N$ ($N$ is the number of emitters in PAA) and presents a radiation matrix for the given direction:

$$a_{i,j} = f_{i}^{(\theta)} f_{j}^{(\theta)} + f_{i}^{(\phi)} f_{j}^{(\phi)},$$

$f_i$ is a partial field i.e. the field radiated by an antenna system where $i$ – th emitter is fed by unit current, while other emitters are not.

It is easy to see that the maximization of $F$ in the form (1) does not make a sense without constraints. We can introduce constraints from an assumption that the power which is provided on emitters is limited by using matrices $B^{(k)}$:

$$B^{(k)} = \frac{1}{4P_m^{(k)}} \left( Z + P^{(k)} + P^{(k)}Z \right),$$ \hspace{1cm} (2)

where $k = 1, \ldots, n$ is the index of emitter where the power should be constrained, $n$ is a number of PAA’s feeding points where providing power is constrained (in the general case $n$ can be
not equal to \( N \), \( P_m^{(k)} \) is a nominal power that can be provided for \( k \)-th emitter, \( Z \) is the resistances matrix of antenna system, \( P^{(k)} \) is a matrix-projector which has the only nonzero element \( P_{k,k}^{(k)} = 1 \). Partial fields and resistance matrix define the mutual influence of emitters on each other.

There is a general problem statement in terms of complex currents feeding each emitter [7, 8]. This problem can also be reformulated in the real numbers [9] which is more applicable for usage in a solving algorithm. In the latter case the problem is presented in the following form:

\[
\begin{aligned}
& x^T G x \rightarrow \text{max}, \\
& 0 \leq x^T H^{(1)} x \leq 1, \\
& \vdots \\
& 0 \leq x^T H^{(n)} x \leq 1, \\
& i \in \mathbb{R}^{2N}.
\end{aligned}
\]  

As \( x \) we introduce a real representation of currents vector \( i \) and it has a dimension equal to \( 2N \). Real matrix \( G \) has a size \( 2N \times 2N \) and is a real representation of the matrix \( A \). Each of real matrices \( B^{(k)}, k = 1, n \), has size \( 2N \times 2N \) and is a real representation of the matrix \( B^{(k)} \).

Global optimum solution of the mathematical programming problem (3) can be found by the branch and bound method [10, 11] or by methods of DC-programming [12, 13]. Local optimum solution can be found by the means of gradient optimization or Newton’s method [14]. In the case of large-dimensional problems different metaheuristics can be applied (see [15, 16]).

3. Computational experiment

In this paper we study ring-structured shortwave PAA s. The measurement of resistances matrix is a trivial problem while the measurement of partial fields requires a lot of receivers for each of possible radiation directions. The usage of high symmetric design of PAA allows to perform a calculation for one direction and easily adopt it for any other direction. A number of models with counterweights system which were raised above the ground up to 2m. This distance between the counterweights and the ground was introduced to decrease an influence of ground loss (see [17]) on calculation results.

We studied how total gain in the given direction depends on the radio-frequency and on the density of counterweights system. The total gain is the sum of partial gains for any two orthogonal polarizations. The density of counterweights system was changed by defining a number of longitudinal and transversal wires related to the same emitter. The frequency was changing from 5 to 30MHz. The calculations were performed on PAA s which consists of 8 emitters. To calculate radiation matrix and resistance matrix NEC-2 antenna modeling package [18] was used. BARON solver in the GAMS package was chosen as a solving. The results of directivity optimization in the given direction were compared to a total gain of a single emitter with the same counterweights system. The density of counterweights system we will denote in the format long : trans, where long - number of longitudinal wires related to one emitter and trans - a number of transversal wires. Height of each BVM is 15m. The direction on optimization is 70° as polar angle and 45° as azimuthal angle.

On Fig. 2 it is shown how the PAA’s total gain depends on the radio-frequency. We can observe that on frequency values equal to 5 and 30MHz antenna system directivity is not improved significantly. Also we can see that in the general increase of counterweights system density leads to increase of total gain. The only exception is an array with counterweights system density equal to 6 : 9 at frequency 15MHz where we can observe an unexpected gain decrease. One of the explanation this decreasing is the BARON solver does not prove the globality of this solution.

On the Fig. 3 it is shown how the difference of PAA total gain and single emitter total gain is changing with a frequency rise. One of the most noticeable results here is that at frequency
Figure 2. PAA total gain in direction 70:45 depending on frequency

Figure 3. Comparison of the PAA and single emitter total gain in direction 70:45 for different frequencies.

25MHz the gains of PAA significantly greater than the gain of a single emitter. The reason of this result will be explained later in the beam pattern comparison. On frequency equal 5MHz total gain does not exceed significantly the gain of a single emitter, but on the 10MHz the difference rises up to 7.53dBi. Even at the 30MHz, where the directivity was not optimized significantly, the gain difference rises up to 6.63 in the best case and up to 4.84 in the worst case.

Now let us compare beam patterns for the PAA with counterweight system density 5 : 7 as a one of the typical results of optimization.

At frequency 5MHz (see Fig. 4) we can observe that the maximum of directivity in the case of PAA drops on 70° and it exceeds the corresponding value of single emitter by 1.33 dBi. Using
of counterweight system with density 6.9 allows to increase this factor on this frequency up to 3.14 dBi. But as mentioned above, on this frequency there was no significant improvement.

The result of optimization is more noticeable at frequency 10MHz (see Fig. 5): back lobe is significantly lower and the difference between total gain of PAA and total gain of single emitter rises approximately up to 8 dBi. The similar result can be observed at 15MHz.

At the 20MHz we can observe that both single emitter and PAA decreases the total gain relative to 15MHz (see Fig. 2). Beam pattern for this frequency is shown on Fig. 6.

Curious result is observed at 25MHz (see Fig. 7) where total gain of PAA is significantly greater than the corresponding value of a single emitter. A comparison of their beam patterns shows that in the case of single emitter the radiation in required direction is very small while the maximum of PAA’s radiation is attained in to the required direction. It cannot be possible to avoid this lack of radiation in optimization direction without consideration of mutual influence. This means that mutual influence of emitters radiation should not be neglected because it can
significantly change the plan of a beam pattern.

At last let us observe how horizontal plan of beam pattern is changing with a frequency rise (see Fig. 8). Optimization direction is $45^\circ$. Here we can observe that at frequency equal to $5\,\text{MHz}$ the beam pattern has nearly oval shape. Further frequency increase up to $15\,\text{MHz}$ leads to very directed shape. But then frequency rise leads to a very complicated beam pattern shape and gain maximum in the required direction becomes less noticeable.

4. Conclusion

In this paper we study the directivity maximization of ring-structured short-wave PAAAs where mutual influence of emitters radiation was taken into consideration. The following results were obtained:

- Using of too sparse counterweights system leads to losing of total gain.
- Further increase of counterweights system density can lead to no significant rise of total gain.
- Mutual influence of emitters radiation can significantly change the total gain in required direction.
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References

[1] Hansen R 2009 Phase array antennas vol 213 (John Wiley & Sons)
[2] Kudzin V, Lozovsky V and Shlyk N 2013 2013 IX International Conference on Antenna Theory and Techniques (IEEE) 252–253
[3] Wilensky R 1988 IEEE transactions on broadcasting 34 201–209
[4] Yin Y and Deng J 2007 Electronic Engineer 33 31–33 in Chinese
[5] Sazonov D M 1988 Antennas and microwave devices (M:High.sc.) (in Russian)
[6] Indenbom M, Zhurttun V, Sharapov A and Zonov A 2018 IX International Conference on Optimization and Applications (OPTIMA 2018) 273–285
[7] Yurkov A S 2014 Optimization of excitation of transmitting phased antenna arrays of decameter wavelength range (ONIIP, Omsk) (in Russian)
[8] Yurkov A S 2016 Radio communication technology 46–53 (in Russian)
[9] Ereemeev A V, Tyunin N N and Yurkov A S 2019 MOTOR 2019 11548
[10] Horst R and Tuy H 2013 Global optimization: Deterministic approaches (Springer Science & Business Media)
[11] Tawarmalani M and Schinidis N V 2004 Mathematical programming 99 563–591
[12] Horst R and Pardalos P M 2013 Handbook of global optimization vol 2 (Springer Science & Business Media)
[13] Strekalovsky A S 2017 Journal of Optimization Theory and Applications 173 770–792
[14] Himmelblau D M 1972 Applied nonlinear programming (McGraw-Hill Companies)
[15] Eberhart R and Kennedy J 1995 Proceedings of the IEEE international conference on neural networks vol 4 (IEEE) 1942–1948
[16] Storn R and Price K 1997 Journal of global optimization 11 341–359
[17] Yurkov A S 2014 Technika radiovyazi 78–84 (in Russian)
[18] Burke G J and Poggio A J Numerical electromagnics code URL https://www.nec2.org/