Abstract - In this paper we propose a method to design the decoupling and matching network for the monopole four-square array antenna on a finite ground plane. It has been found that the mutual coupling of the antenna elements placed on a finite ground plane (chassis) depends strongly on the dimensions of the chassis. To model the chassis effects, in the second step, we designed an Artificial Neural Network (ANN) which allowed us to optimize the chassis size that leads to an even better result for the proposed decoupling network. In this way the optimization problem for this array antenna is introduced using the method of genetic algorithms.

I. INTRODUCTION

In the previous paper [1], the optimization problem for a “Monopole Four-Square Array Antenna” has been defined and optimization was performed using the method of Genetic Algorithm (GA) [2]. Under the assumption that the antennas were mounted on an infinite ground plane we observed that the mutual coupling between the antennas distorted the beam patterns and reduced the radiation efficiency. In this paper we propose a method to design a decoupling network for the Monopole Four-Square Array Antenna on a finite ground plane size. As shown in [3], the ground plane can heavily influence the mutual coupling of the antenna elements placed on it, in principle due to the excitation of current modes on its surface which can resonate at certain length and width dimensions. Introducing a cost-function, an optimization problem has been defined to find the minimum coupling between the antennas. In this paper we have taken the next step. Then to improve the decoupling results, additional lumped elements (Capacitors/Inductors) have been considered between adjacent and opposite antennas. The optimal value of each capacitor/inductor as well as the length and diameter of each monopole antenna, array distance and ground plane dimensions have been found after optimizing a cost function, based on just the “maximum decoupling” criterion. The next, more sophisticated step employs seven criteria: maximum decoupling, minimum envelope correlation of beams, maximum front-to-back ratio, best fit to the ideal secant-squared elevation pattern, suitable beam crossover levels between 3dBi and 6 dBi, maximum directivity and maximum efficiency of each antenna. For this optimization problem, we consider four realistic monopole antennas of variable length, diameter and array distance on a finite ground plane with variable dimensions. Six variable capacitors/inductors have been also used between neighbouring and opposite antenna ports to accomplish the RF decoupling network. The current and voltage excitations of the monopole antennas are related via the admittance matrix Y, where the source open-circuit voltages of the feed network can be also varied over a certain range. In this step a high accuracy hierarchical neural network structure [4] has been designed to model the ground plane effects and utilize this model in our cost function. The inputs to our neural network model consist of: Antenna length, Antenna diameter, Array distance, Chassis length, Chassis height, neighbouring capacitance/inductance and opposite capacitance/inductance and the outputs consist of the admittance matrix elements of the array with lumped elements mounted on the finite chassis. Finally the optimized values of neural network inputs as well as the source voltages have been found using a GA in our full degree optimization.

II. COUPLING EFFECTS OPTIMIZATION

The Monopole Four-Square Array Antenna mounted on an infinite ground plane is depicted in Fig. 1. The frequency dependent impedance matrix Z characterises the mutual coupling between the elements of array, and according to

\[
\begin{bmatrix}
  V_1 \\
  V_2 \\
  V_3 \\
  V_4 \\
\end{bmatrix} =
\begin{bmatrix}
  Z_{11} & Z_{12} & Z_{13} & Z_{14} \\
  Z_{12} & Z_{11} & Z_{13} & Z_{14} \\
  Z_{13} & Z_{12} & Z_{11} & Z_{14} \\
  Z_{14} & Z_{13} & Z_{12} & Z_{11} \\
\end{bmatrix}
\begin{bmatrix}
  I_1 \\
  I_2 \\
  I_3 \\
  I_4 \\
\end{bmatrix}
\]  

relates the port-voltages \( V \) to the driving port currents \( I \). \( Z \) is the mutual impedance between elements \( i, j \), \( Z_e \) is the self impedance of element \( j \). Some relationships can be used [5] to give the self impedance as a function of the length and diameter of each antenna and mutual impedance as a function of the antenna length and element spacing of array.

The reduction of the ground plane has two major detrimental effects. The first is an increase in back lobe radiation due to diffraction and the second is a change in the impedance of the antenna, which will increase the return loss.
Furthermore, in an investigation of radiation properties of a small phased array antenna on a chassis it was found that radiation pattern, radiation resistance of the elements and the mutual coupling of the elements depend strongly on the dimensions of the ground plane [3].

A. Optimize the parameters of each antenna, array and chassis size

To reduce the couplings between the antennas, in the first step we have considered four monopole antennas with element spacing ($d$), length of ($L$) and diameter of ($D$) mounted on a small ground plane size with dimensions of ($X$)×($X$)×($H$), as shown in Fig.2. Using CST optimization toolbox, the variables $d$, $L$, $D$, $X$ and $H$ have been optimized to find the minimum values of mutual impedances (real and imaginary parts separately):

$$J_1(d, L, D, X, H) = W_1(Z_{12}^2 + W_2(Z_{13}^2)$$  \hspace{1cm} (2)

The following conditions have been considered in our optimization problem:

$$0.252 \leq d/\lambda \leq 0.350 \quad \text{(Corridor in the first step [1])}$$  \hspace{1cm} (3)

$$0.150 \leq L/\lambda \leq 0.350$$  \hspace{1cm} (4)

$$0.004 \leq D/\lambda \leq 0.04$$  \hspace{1cm} (5)

$$0.0015 \leq H/\lambda \leq 0.05$$  \hspace{1cm} (6)

$$0.4 \leq X/\lambda \leq 1.4$$  \hspace{1cm} (7)

B. Decoupling and Matching Network

In the second part we have connected six lumped capacitors/inductors between adjacent antenna ports to accomplish the RF decoupling and matching network (DMN) as shown in Fig.3. Passive DMN compensate for the problem of mutual coupling between the radiators. The decoupling network consists of the components $jB_1$ (Capacitance $C_1$ or inductance $L_1$) between neighbouring antennas and $jB_2$ (Capacitance $C_2$ or inductance $L_2$) between opposite antennas. Avoiding the crossing of two transmission lines between opposite antennas, a cross-coupler, also known as 0 dB coupler, has been assumed between the antenna ports [6].

Initially ignoring transmission line effects, the following admittance matrix describes the DMN:

$$Y_2 = \begin{bmatrix} 2jB_1 + jB_2 & -jB_1 & -jB_2 & -jB_1 \\ -jB_1 & 2jB_1 + jB_2 & -jB_1 & -jB_2 \\ -jB_2 & -jB_1 & 2jB_1 + jB_2 & -jB_1 \\ -jB_1 & -jB_2 & -jB_1 & 2jB_1 + jB_2 \end{bmatrix}$$  \hspace{1cm} (8)

The admittance matrix of the decoupled array can be also written as:

$$Y^D = \begin{bmatrix} y_{11}^D & y_{12}^D & y_{13}^D & y_{14}^D \\ y_{12}^D & y_{11}^D & y_{13}^D & y_{14}^D \\ y_{13}^D & y_{14}^D & y_{11}^D & y_{12}^D \\ y_{14}^D & y_{13}^D & y_{12}^D & y_{11}^D \end{bmatrix}$$  \hspace{1cm} (9)

If we consider the network shown in Fig.3 on an infinite ground plane, then the admittance matrix (9) can be written as:

$$Y^D = \begin{bmatrix} y_{11}^D & y_{12}^D & y_{13}^D & y_{14}^D \\ y_{12}^D & y_{11}^D & y_{13}^D & y_{14}^D \\ y_{13}^D & y_{14}^D & y_{11}^D & y_{12}^D \\ y_{14}^D & y_{13}^D & y_{12}^D & y_{11}^D \end{bmatrix} = Z^{-1} + Y_2$$  \hspace{1cm} (10)

For decoupling the array, the mutual admittance of the decoupled system ($Y_{12}^D$ and $Y_{13}^D$) should be zero. Solutions for

![Fig.1 Four-square array for multi-beam applications](image1)

![Fig.2 Four-monopole array antenna on a finite ground plane](image2)

![Fig.3 RF-decoupling network using a cross-coupler](image3)
$B_1$ and $B_2$ can be obtained by minimizing the following cost function (real and imaginary parts):

$$J_2(B_1, B_2) = W_1 \left( y_{11}^R \right)^2 + W_2 \left( y_{11}^I \right)^2 \quad (11)$$

In our sophisticated case, we have considered a finite chassis and the decoupling admittance matrix (9). Four monopole antennas with element spacing ($d$), length of ($L$) and diameter of ($D$) and six capacitors (with capacitance $C_i/C_j$), Inductors (with inductance $L_i/L_j$) mounted on a small ground plane with dimensions of ($X$)$\times$($X$)$\times$($H$), have been considered in our optimization problem, as shown in Fig.4. Using CST optimization toolbox, the variables $d$, $L$, $D$, $X$, $H$, $C_n$ and $L_m$ have been optimized to minimize the following cost function:

$$J_3 = \min \left[ \text{Cost}(C_1, L_2), \text{Cost}(C_2, L_4), \text{Cost}(C_1, L_4), \text{Cost}(C_2, L_2) \right] \quad (12)$$

where:

$$\text{Cost}(C_n, L_m) = \sum_{i=1}^{4} \sum_{k=1}^{4} W_k (Y_{ik}^D)^2 \quad (13)$$

$Y_{ik}^D$ is the real and imaginary part of the mutual admittances of decoupling admittance (9).

![Fig.4 Four-monopole array antenna on a finite ground plane with lumped elements between them](image)

The following conditions have been considered in our optimization procedure:

$$1 \text{pf} \leq C_n \leq 10 \text{pf} \quad (14)$$

$$1 \text{nm} \leq L_{ij} \leq 10 \text{nm} \quad (15)$$

**III. FULL DEGREE OPTIMIZATION**

In this step we have designed a neural network to model the system shown in Fig.4 and utilized it in our Full degree optimization problem.

**A. Hierarchical Neural Network model**

In the neural network research community, an advanced concept called Combining Neural Networks that addresses issues of neural network accuracy and training efficiency is being exploited [4]. Based on this concept, a hierarchical neural network approach was developed, using existing microwave information /knowledge in the formulation of sub-modules (networks) and in defining the interactions between modules. The applied hierarchical neural network structure for the Four-monopole array antenna on a finite ground plane with lumped elements (Fig. 4) is shown in Fig.5. We have chosen 10 low-level neural modules $L_n$, 10 knowledge hubs $U_i$ and 2 Multilayer Perceptron (MLP) for high-level neural module $H$. Seven variables: Antenna length $L$, Antenna diameter $D$, Array distance $d$, Chassis length $X$, Chassis height $H$, neighbouring capacitance/ inductance $C_i/L_j$ and opposite capacitance/ inductance $C_j/L_i$ have been considered as the input vector $X$ to our model and the output vector $Y$ consists of 10 variables: Self admittances ($Y_{11}$, $Y_{22}$, $Y_{33}$ and $Y_{44}$) and mutual admittances ($Y_{12}$, $Y_{13}$, $Y_{14}$, $Y_{23}$, $Y_{24}$ and $Y_{34}$) of the complete array (real and imaginary):

$$Y^D = \begin{pmatrix}
Y_{11}^D & Y_{12}^D & Y_{13}^D & Y_{14}^D \\
Y_{12}^D & Y_{22}^D & Y_{23}^D & Y_{24}^D \\
Y_{13}^D & Y_{23}^D & Y_{33}^D & Y_{34}^D \\
Y_{14}^D & Y_{24}^D & Y_{34}^D & Y_{44}^D
\end{pmatrix} = f(L, D, d, X, H, C_i/L_1, C_2/L_2) \quad (16)$$

Based on results calculated using the CST simulator, we have recorded 150 samples, 125 data for training the model and 25 data for testing the accuracy of model.

![Fig.5 The hierarchical neural network structure](image)

**B. Optimization Problem**

Finally we have implemented this neural network model in our ultimate optimization problem. In this step we consider the system shown in Fig. 4 of variable Antenna length $L$, Antenna diameter $D$, Array distance $d$, Chassis length $X$, Chassis height $H$, neighbouring capacitance/ inductance $C_i/L_1$ and opposite capacitance/ inductance $C_j/L_2$. In this step we assumed that the source impedance of the feed network $Z_o$ is fixed to 50 $\Omega$ but the source voltages $V_o$ ($i=1,...,4$) can be varied over the certain range (18) and (19) [1]:

$$Z_o = 50 \Omega \quad (17)$$
The excitations $I_i (i=1,...,4)$ at the input terminals of each antenna can be expressed as a function of $Z_o, V_o (i=1,...,4)$ and admittance matrix (16).

The following cost function has been considered in our final optimization problem:

$$J = \frac{(W_1 F_i + W_2 F_2 + W_3 F_3 + W_4 F_4)}{\varepsilon + (W_5 F_5 + W_6 F_6 + W_7 F_7)}$$

where $F_i$ are the seven criteria expressed as below:

- $F_1(I_i,d,L):$ Minimum envelope correlation of beams [1]
- $F_2(I_i,d,L):$ Best fit to the ideal secant-squared elevation pattern [1]
- $F_3(I_i,d,L):$ Suitable beam crossover level (between 3dBi and 6dBi) [1]
- $F_4(I_i,d,L):$ Minimum mutual coupling, expressed in (16)
- $F_5(V_o,d,L):$ Maximum efficiency of each antenna [1]
- $F_6(I_i,d,L):$ Maximum directivity [1]
- $F_7(I_i,d,L):$ Maximum Front-to-Back ratio [1]

Equations (4), (5), (6), (7), (14), (15), (17), (18) and (19) are considered for our optimization conditions.

IV. OPTIMIZATION RESULTS

A. Coupling effects optimization

The Cost function (2) with conditions (3), (4), (5), (6) and (7) has been minimized using a GA with generation of 35 individuals each, $P_{crossover} = 0.75$ and $P_{mutation} = 0.04$ . Table I shows the optimization results for the array without considering the decoupling-matching network. Using the CST optimization toolbox, the Cost function (12) with conditions (3), (4), (5), (6), (7), (14) and (15) has been also minimized. Table II shows the optimization results for the array with decoupling-matching network. The simulation results of the scattering parameters of the array on a finite ground plane with and without the decoupling-matching network are shown in Fig. 6. The chosen frequency of operation of the array is at 3 GHz.

The magnitude of $S_{11}$ of each antenna without the decoupling network is approximately -13 dB at the operating frequency. With the decoupling network, return losses are reduced to -27 dB for $S_{11}$ and -18 dB for $S_{22}, S_{33}$ and $S_{44}$.

(Note that return losses have not been considered in our cost function)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$d^{op}$</th>
<th>$L^{op}$</th>
<th>$D^{op}$</th>
<th>$H^{op}$</th>
<th>$X^{op}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>$0.28\lambda$</td>
<td>$0.20\lambda$</td>
<td>$0.006\lambda$</td>
<td>$0.03\lambda$</td>
<td>$0.5\lambda$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$C_{1}^{op}$</th>
<th>$L_{2}^{op}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>$1.12 pf$</td>
<td>$3.03 nH$</td>
</tr>
</tbody>
</table>

Table I: Optimization results for the array without decoupling network obtained by GA

Table II: Optimization results for the array with decoupling network obtained by CST optimizer

The magnitude of $S_{21}$ and $S_{31}$ of the array without decoupling network are approximately -11 dB and -18 dB respectively. With decoupling network the magnitudes of $S_{21}, S_{31}, S_{24}, S_{34}$, $S_{13}$ and $S_{24}$ are less than -30 dB. These results show that to remove the effect of mutual coupling completely, we have to use an optimized DMN.

B. Full degree optimization

The variation of “Average Testing Error” for 25 testing data during the training process (with 125 samples) of the
designed hierarchical neural network model is shown in Fig. 7. As training data become more than 10^6, the error remains approximately at 0.5%. This low average error on test data shows the accuracy of this model.

![Fig.7 Hierarchical neural network model accuracy](image)

For the purpose of optimizing the cost function described in (20) with conditions (4), (5), (6), (7), (14), (15), (17), (18) and (19) a genetic Algorithm with generations of 45 individuals each, $P_{\text{crossover}} = 0.75$ and $P_{\text{mutation}} = 0.04$ was used. Table III shows the full degree optimization results.

**TABLE III**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$d_{\text{op}}$</th>
<th>$L_{\text{op}}$</th>
<th>$D_{\text{op}}$</th>
<th>$H_{\text{op}}$</th>
<th>$X_{\text{op}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.281$\lambda$</td>
<td>0.202$\lambda$</td>
<td>0.006$\lambda$</td>
<td>0.038$\lambda$</td>
<td>0.53$\lambda$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>$L_{\phi}$</th>
<th>$V_{10}$</th>
<th>$V_{20}$</th>
<th>$V_{30}$</th>
<th>$V_{40}$</th>
<th>$V_{50}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{1}$</td>
<td>2.82pf</td>
<td>3.7nH</td>
<td>1.31</td>
<td>14.1°</td>
<td>1.04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>$\theta$</th>
<th>$\phi$</th>
<th>$\theta$</th>
<th>$\phi$</th>
<th>$\theta$</th>
<th>$\phi$</th>
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<tbody>
<tr>
<td>$\angle V_{20}$</td>
<td>84.2°</td>
<td>86°</td>
<td>192°</td>
<td>78°</td>
<td>73°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The radiation pattern (x-y plane $\theta = 90^\circ$) of the monopole four-square array antenna, corresponding to the value of optimized parameters in Table 3, is shown in Fig. 8. The Radiation efficiency of 0.98 has been found for each antenna. The return losses of antennas are between -15 dB and -25 dB and the other S-Parameters which are less than -23 dB show the decoupling of the array.

![Fig.8 Radiation pattern of the array](image)

As an experimental example, the radiation pattern of a squared array of four monopole antennas which are mounted on a large ground plane size is shown in Fig. 9. [1]

We can see an improvement in the side lobe level and front-to-back ratio in optimized radiation pattern.

![Fig.9 Experimental non optimized radiation pattern on a large ground plane](image)

**C. Conclusions**

This paper has shown that the mutual coupling of four-square monopole antenna on a finite ground plane can be removed by the use of an optimum decoupling network. The simulation results confirmed that the array was matched and decoupled. In a next step an artificial neural network (ANN) has been developed and tested for Monopole Four-Square Array Antenna design. It transforms the data containing the Antenna length , Antenna diameter , Array distance , Chassis length , Chassis height , neighbouring decoupling capacitance/inductance and opposite decoupling capacitance/ to the admittance matrix of the array mounted on a finite ground plane considering the decoupling network. The neural model presented in this work gives accurate results and requires no tremendous computational efforts. Finally this model has been utilized in full degree optimization problem for a Monopole Four square array antenna on a finite ground plane with decoupling network and applying additional performance requirements. The technique uses the genetic algorithm to determine the optimal parameters. This approach has also the advantage of escaping the local solutions; it tends to produce global optimal results without requiring a great deal of information about the solution domain.

**REFERENCES**


