Phased arrays in communication system based on Taguchi-neural networks

A. Smida¹, R. Ghayoula¹², N. Nemri¹, H. Trabelsi¹, A. Gharallah¹ and D. Grenier²

¹Unit of Research in High Frequency Electronic Circuits and Systems, Faculty of Mathematical, Physical and Natural Sciences of Tunis, Tunis El Manar University, Tunis, Tunisia
²Department of Electrical and Computer Engineering, Laval University, Québec QC, Canada

SUMMARY

Phased antenna array design is one of the most important electromagnetic optimization problems. This research combined the Taguchi method and artificial intelligence methods, used them as the prediction tool in designing parameters for the communication system, and then constructed a set of the optimal parameter analysis flow and steps. In this paper, we present an application of artificial neural networks in the electromagnetic domain. We particularly look at the multilayer perceptron network, which has been the most used of artificial neural networks architectures both in the electromagnetic domain and in the Taguchi optimization technique and describes the Taguchi method to optimize the excitations elements of the linear array to produce a radiation pattern with minimum side lobe level and null placement control. This paper investigates how the implementation of the signal processing in hardware affects the performance of the adaptive array antenna. The investigation is confined to uplink or receive antenna array only. Results of a prototype of antenna array with feeding values designed using the proposed techniques are also presented. Copyright © 2013 John Wiley & Sons, Ltd.

Received 14 June 2012; Revised 17 May 2013; Accepted 17 July 2013

KEY WORDS: neural network; Taguchi; synthesis method; phased antenna array; steering beams; multiple steering; interference nulling

1. INTRODUCTION

Phased array antennas consist of multiple antenna elements, which are fed coherently and use variable phase or time-delay control at each element to scan a beam to given angles in space. Variable amplitude control is sometimes also provided for pattern shaping. Arrays are sometimes used in place of fixed aperture antennas, because the multiplicity of elements allows more precise control of the radiation pattern, thus resulting in lower side lobe level (SLL) or careful pattern shaping. However, the primary reason for using arrays is to produce a directive beam that can be scanned electronically. Although arrays with stationary beams and multiple stationary beams will be discussed in this text, the primary emphasis will be on those arrays that are scanned electronically [1–4]. The network can be that of any of the wireless communication technologies such as global system for mobile communications, code division multiple access, wireless local loop, WAN, WiFi, and WiMAX [5–8].

Taguchi’s method started after the Second World War. The Japanese telephone system had been extremely poor and totally unsuitable for long term communication purposes. To improve the
system, the Japanese have founded the electrical communication laboratories with Dr. Genichi Taguchi who was in charge of improving and enhancing the product quality. Dr. Taguchi noticed that a great deal of time and money was expended on engineering experimentation and testing, so he started to develop new methods to optimize the process of engineering experimentation, and he believed that the best way to improve the quality was to design and build it into product. Dr. Taguchi developed the technique that was known as Taguchi’s method. His main contribution does not lie in the mathematical formulation of the design of experiments, but rather in the accompanying philosophy. Besides that, his concept produced a unique and powerful improvement technique that differs from traditional practices. Taguchi’s method was introduced in [9] to the electromagnetic community and demonstrated its great potential in electromagnetic optimizations. The proposed optimization procedure has been applied in designing a linear antenna array with a sector beam pattern and a microstrip band-stop filter [9, 10]. The desired antenna pattern and frequency response of band-stop filter were successfully achieved. Compared with other optimization techniques, such as the genetic algorithm and particle swarm optimization, Taguchi’s method is easy to implement, and can quickly converge to the optimum solution.

In recent years, artificial neural networks (ANNs) have been developed to mimic the behavior of biological neural nets, and have successfully solved problems through generalization of a limited quantity of training data, overall trends in functional relationships. ANNs have been used in a wide range of applications and proven to be effective in performing complex functions in various fields. ANNs can be constructed to perform classification [11], approximate equations [12], and predict values [13, 14]. In predictive modeling, the objective is to map a set of input patterns on to a set of output patterns. In recent years, many researches have been conducted on the basis of the Taguchi method [15–18] for electronic packages and in predicting the antenna weights (amplitude and phase).

In [19], the authors described a new electromagnetic optimization technique using Taguchi’s method and apply it to linear antenna array design. Taguchi’s method was developed on the basis of the orthogonal array (OA) concept, which offers systematic and efficient characteristics.

In this paper, a global optimization technique based on Taguchi’s method and neural networks (NNs) technique are applied so as to determine the excitation coefficients and the resultant pattern for a broadside discrete element array whose array factor will directly approximate the symmetrical sectoral pattern. The implementation system is described in detail, and linear antenna array examples are discussed to demonstrate its validity. Optimized results show that the desired array factors, a null controlled pattern, and a sector beam pattern are effectively obtained. It is found that NN is an excellent candidate for optimizing diverse applications, as it is easy to realize and converges to the desired patterns rapidly. The paper is organized as follows: The synthesis problem formulation using Taguchi’s method is presented in Section 2. Multilayer networks and back-propagation algorithm is developed in Section 3. Section 4 shows the novel design of phased antenna array with the simulation and measurement result, and finally, Section 5 makes conclusions.

2. ELECTROMAGNETIC OPTIMIZATION USING TAGUCHI’S METHOD

2.1. Antenna array factor formulation

The radiation characteristics of antennas have mostly to do with the far field region. In this region, the field expression is a multiplication of two parts. One part contains the distance $r$ dependence of the observation point, and the other contains its spherical coordinate angles $\theta$ and $\varphi$ dependence (Figure 1).

The angular distribution of the field is independent of the distance $r$. For a typical antenna element, the far electric field is

$$E_n(r) \approx j \sigma \mu \frac{e^{-j\beta r}}{4\pi r} f_n(\theta, \varphi) \quad (1)$$
The angular-dependent vector $f_n(\theta, \phi)$ gives the directional characteristics of the $n$th element electric field [20, 21]:

$$f_n(\theta, \phi) = I_n f(\theta, \phi)$$  \hspace{1cm} (2)

$f(\theta, \phi)$ is called the ‘pattern function’ of the element with the complex excitation of the $n$th element of the array.

$$E(r) = -j\sigma\mu \frac{e^{-j\beta r}}{4\pi r} f(\theta, \phi) \sum_{n=1}^{N} I_n e^{j\beta r_n \cos \xi_n}$$  \hspace{1cm} (3)

Where

- $\varphi, \theta, \phi_n$ are the spherical coordinates of a convenient reference point of the $n$th element, and
- $r_n, \theta_n, \phi_n$ are the spherical coordinates of a convenient reference point of the $n$th element, and
- $\cos \xi_n = \sin \theta \sin \theta_n \cos (\phi - \phi_n) + \cos \theta \cos \theta_n$.

One of the major advantages of array antennas is that the array excitation can be closely controlled to produce extremely low-side lobe patterns or very accurate approximations of chosen radiation patterns. Many intricate procedures have been developed for synthesizing useful array factors. These methods fit into three main classes of synthesis: synthesis of various sector patterns that are usually many beamwidths wide, synthesis of low-side lobe, narrow-beam patterns, and procedures that optimize some array parameter, such as gain and signal-to-noise ratio, subject to some constraint on the SLL or the existence of outside noise sources.

### 2.2. Taguchi optimization method

Taguchi’s optimization method will be briefly described here. The interested reader may consult [19] for more details. The steps taken in Taguchi’s optimization can be summarized as follows.
2.2.1. **Initializing the problem.** The optimization procedure begins with the problem initialization, which includes the selection of a proper OA, and an appropriate design of the fitness function. The selection of an OA depends on the number of input parameters of the optimization problem, and the number of levels of each parameter. Usually three levels are necessary for each input parameter to describe the nonlinear effect.

2.2.2. **Designing input parameters using an orthogonal array.** In this step, the input parameters are selected to guide the experiments (i.e., the evaluation of the fitness function). For an OA with \( s = 3 \), the value of level 2 for each parameter is chosen at the center of the optimization range corresponding to that parameter. Then, the values of the other levels (1 and 3) are respectively evaluated by subtracting and adding a specific ‘level difference’ (LD) to the value of level 2. The equation that determines the LD in the first iteration is taken as [22–24].

\[
LD_1 = \frac{(\text{max} - \text{min})}{s + 1}
\]  

(4)

where ‘max’ and ‘min’ are the upper and lower bounds of the optimization range, respectively.

2.2.3. **Conducting experiments.** After converting the OA entries to proper input values, the fitness function for each experiment can be calculated analytically or through numerical simulations. The fitness value is used to calculate the corresponding S/N ratio (\( \eta \)) in Taguchi’s method through the following formula [24, 25]:

\[
\eta = -20 \log(\text{Fitness}) \ (dB)
\]

(5)

After conducting all the experiments and finding the fitness values and the corresponding S/N ratio, a response table is built by averaging the S/N for each parameter \( n \) and level \( m \) using [17]

\[
\eta(m, n) = \frac{1}{N} \sum_{i, \text{OA}(i,n)=m} \eta_i
\]

(6)

2.2.4. **Identifying optimal level values and conducting confirmation experiment.** When the response table is established, the optimal level for each parameter can be identified by finding the largest S/N ratio. Next, a confirmation experiment is carried out by using the combination of the optimal level values \( \phi_{n|_{i}^{\text{opt}}} \).

2.2.5. **Reducing the optimization range.** If the termination criteria are not satisfied, the optimal level for the current iteration will be the center of the next iteration.

\[
\phi_{n|_{i+1}} = \phi_{n|_{i}}^{\text{opt}}
\]

(7)

Also, the optimization range for the next iteration is minimized by multiplying the current LD by the reducing rate (\( rr \)) (Eq. 5). \( rr \) can be set between 0.5 and 1 according to the problem [27]. So, for the \((i + 1)^{\text{th}} \) iteration [17–26],

\[
LD_{i+1} = RR(i) \times LD_1 = rr^i \times LD_1
\]

(8)

Where \( RR \ (i) = rr^i \) is called the reduced function.
2.2.6. Checking the termination criteria. Each time the number of iterations increases, the LD of each element decreases. So, the level values are near to each other, and the fitness value of next iteration is close to the fitness value of the current iteration. The next equation can be used as a termination criterion for the optimization procedure [26].

\[
\frac{LD_{i+1}}{LD_i} \leq \text{converged value}
\]  

(9)

Usually, the converged value can be set from 0.001 to 0.01 depending on the problem. If the design targets are achieved or Eq. (6) is satisfied, the optimization process will finish. Finally, the aforementioned steps are repeated until a specific termination criterion is achieved or a specific number of iterations are reached [27].

Taguchi’s method is used in the synthesis of linear antenna array to minimize the maximum SLL by controlling only amplitude parameter. Figure 2 presents the antenna array geometry.

Which has 10 equally spaced elements along the axis x. The element spacing is half-wavelength, and the excitations of array elements are symmetric with respect to the axis y. The excitation amplitude of the five elements will be optimized in the range of (0, 1) to shape the antenna pattern.

For a 10-element symmetrical array, the array factor can be written as [19–28]:

\[
AF(\theta) = 2 \sum_{n=1}^{5} A(n) e^{j\phi(n)} \cos[kd(n) \cos \theta]
\]  

(10)

where \(k\) is the wave number; \(A(n)\), \(d(n) = \lambda/2\), and \(\phi(n) = 0\) are the excitation amplitude, location, and phase of the \(n\)th element, respectively.

The following fitness function can be used in the optimization.

\[
\text{fitness} = \min \left( \max \left\{ 20 \log |AF(\theta)| \right\} \right)
\]  

(11)

In Figure 3, every step in the flowchart will be generally explained, and then they will be applied on some examples to show the efficiency of this technique.

In this example, Taguchi’s optimization method will be applied on a 10-element linear array. Tables I (phase synthesis values) and II (amplitude values) hold the optimum values of the phase and amplitude obtained using Taguchi’s method (after 100 iterations).

A laptop with Intel Core (TM) 2 Duo CPU@2.00 GHz and 2.96 Go RAM was used for simulating the Taguchi’s code, and the simulation time was only 12 s.

**Figure 2.** Geometry of an antenna array with 10 identical elements.
Figure 3. Flow chart of Taguchi’s method [17].

Table I. Optimum phase values found by Taguchi’s method.

<table>
<thead>
<tr>
<th>Element number</th>
<th>Example 1: phase values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30°</td>
</tr>
<tr>
<td>1</td>
<td>-173.5644</td>
</tr>
<tr>
<td>2</td>
<td>198.6316</td>
</tr>
<tr>
<td>3</td>
<td>-149.8596</td>
</tr>
<tr>
<td>4</td>
<td>222.3329</td>
</tr>
<tr>
<td>5</td>
<td>-124.7912</td>
</tr>
<tr>
<td>6</td>
<td>124.7912</td>
</tr>
<tr>
<td>7</td>
<td>-222.3329</td>
</tr>
<tr>
<td>8</td>
<td>149.8596</td>
</tr>
<tr>
<td>9</td>
<td>-198.6316</td>
</tr>
<tr>
<td>10</td>
<td>173.5644</td>
</tr>
</tbody>
</table>

Table II. Optimum amplitude values found by Taguchi’s method.

<table>
<thead>
<tr>
<th>Element number</th>
<th>Example 2: optimum amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>±1</td>
</tr>
<tr>
<td>−20 dB</td>
<td>1.0000</td>
</tr>
<tr>
<td>−25 dB</td>
<td>1.0000</td>
</tr>
<tr>
<td>−30 dB</td>
<td>1.0000</td>
</tr>
<tr>
<td>−40 dB</td>
<td>1.0000</td>
</tr>
</tbody>
</table>
3. MULTILAYER NETWORKS AND BACK-PROPAGATION ALGORITHM

Much early research in networks was abandoned because of the severe limitations of single-layer linear networks. Multilayer networks were not ‘discovered’ until much later, but even then, there were no good training algorithms [22]. It was not until the 1980s that back-propagation became widely known.

3.1. Method of training: back-propagation

Define a cost function (e.g., mean square error).

\[ E = \frac{1}{2L} \sum_{k=1}^{L} \left( t^{(k)} - \phi^{(k)} \right)^2 \]  

(12)

Where \( \phi^{(k)} \) is the network output, \( t^{(k)} \) is the desired output, and the activation \( \phi \) at the output layer is given by

\[ \phi = f(Wz) = f_2(Wf_1(wx)) \]  

(13)

and where
- \( z \) is the activation at the hidden nodes.
- \( f_2 \) is the activation function at the output nodes.
- \( f_1 \) is the activation function at the hidden nodes.

**Implementing Back-propagation:**

Create variables for:
- The weights \( W \) and \( w \).
- The net input to each hidden and output node, \( net_i \),
- The activation of each hidden and output node, \( \phi_i = f(\text{net}_i) \), and
- The ‘error’ at each node \( i \).

For each input pattern \( k \):

**Step 1: Forward Propagation**

Compute \( net_i \) and \( \phi_i \) for each hidden node, \( i = 1, \ldots, h \):

\[ net_i = \sum_{r=1}^{n} w_{ri}x_r \text{ and } z_i = f_i(net_i) \]  

(14)

Where \( x_1, x_2, \ldots, x_n \) are the input signals; \( w_{r1}, w_{r2}, \ldots, w_{rn} \) are the synaptic weights converging to neuron \( i \); \( net_i \) is the cumulative effect of all the neurons connected to neuron \( i \).

Compute \( net_j \) and \( \phi_j \) for each output node, \( j = 1, \ldots, m \):

\[ net_j = \sum_{i=1}^{h} w_{ij}z_i \text{ and } \phi_j = f_2(net_j) \]  

(15)

**Step 2: Backward Propagation**

Calculate the error terms (\( \delta_j \) and \( \delta_2 \)) of the nodes in the output and hidden layers, starting from the output layer and continuing with the hidden layers, moving backwards from the output layer to the input layer of the NNs structure. The error terms are calculated according to Eq. (12).
Compute for each output node, $j = 1, \ldots, m$:

$$\delta_{2j} = \left( \phi_{dj} - \phi_j \right) f'_2(\text{net}_j)$$  \hfill (16)

Compute for each hidden node, $i = 1, \ldots, h$:

$$\delta_{ij} = f'_1(\text{net}_i) \sum_{j=1}^{m} w_{ij} \delta_{2j}$$ \hfill (17)

Where $f'_1(\text{net}_i)$ and $f'_2(\text{net}_j)$ present the derivative of the activation function.

Step 3: Accumulate gradients over the input patterns (batch)

$$\frac{\partial E}{\partial w_{ij}} = \frac{\partial E}{\partial w_{ij}} + \delta_{2j} z_i$$

$$\frac{\partial E}{\partial w_{ri}} = \frac{\partial E}{\partial w_{ri}} + \delta_{1i} x_r$$ \hfill (18)

Step 4: After doing Steps 1 to 3 for all patterns, we can now update the weights:

$$w_{ij}(k + 1) = w_{ij}(k) - \mu L \frac{\partial E}{\partial w_{ij}}$$

$$w_{ri}(k + 1) = w_{ri}(k) - \mu L \frac{\partial E}{\partial w_{ri}}$$ \hfill (19)

Where $\mu L$ is a constant of proportionality called the learning rate. Feedback networks (Figure 4) can have signals traveling in both directions by introducing loops in the network. Feedback networks are very powerful and can get extremely complicated. Feedback networks are dynamic; their ‘state’ is changing continuously until they reach an equilibrium point. They remain at the equilibrium point until the input changes, and a new equilibrium needs to be found. Feedback architectures are also referred to as interactive or recurrent, although the latter term is often used to denote feedback connections in single-layer organizations.
As it was shown theoretically that a multilayer NN with only one hidden layer is able to identify a nonlinear function arbitrarily complexes and its derivative, our network thus contains only one hidden layer. The choice of the number of hidden neurons is strongly related to the nature of nonlinearity to model. In our case (Table III), 50 hidden neurons allowed a good convergence of the algorithm and a good precision of the formed neuronal model of two entries and eight exits. The neuron used in this network is the continuous nonlinear neuron whose function of activation is a tan sigmoid function (Table IV).

The architecture of a three-layer NN, shown in Figure 4, consists of an input layer, a hidden layer, and an output layer of summation nodes. The input nodes receive the pre-processed antenna data and broadcast the input vectors to each hidden layer node [24–29].

### 3.2. Neural architecture

To investigate the ideas presented in the previous section, the first step is dividing the space in 15 sectors; repeat every 10° in the interval from −75° to +75° inclusive. More accurate space division sectors can be reached by increasing the number of element arrays. The input vector to the entry of NN $x = [x_1, x_2, \ldots, x_{15}]^T$ is in the form of a 145-bit binary code (one bit for each sector). A bin input of (+1) indicates a source exactly on (main lobe) in the sector. Convergence may then be achieved more rapidly. The proposed scheme (Figure 5) has been tested with excellent results, as it is shown in the following examples (examples 1 and 2). A 10-element antenna array with centers separated is now used for synthesis purposes considering voltages with constant amplitude and variable phase [20].

While maintaining main lobes in the direction of useful signal (at −75° to +75°) (Figure 6) for the reference antenna (10-element antenna array), the results presented in Figures 7 and 8 show simulation radiation patterns with SLL (at −20, −30, and −40 dB respectively).

The optimization is performed using two techniques: Taguchi’s optimization method and NNs technique. The advantage of Taguchi’s optimization technique is the ability of solving problems with a high degree of complexity using a small number of experiments in the optimization process, Taguchi’s method is easy to implement and converges to the desired goal quickly with NNs.

### Table III. Typical values of parameters use in back-propagation algorithm.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neuron in the input layer</td>
<td>$n$</td>
<td>15</td>
</tr>
<tr>
<td>Neuron in the output layer</td>
<td>$m$</td>
<td>10</td>
</tr>
<tr>
<td>Neuron in the hidden layer</td>
<td>$h$</td>
<td>50</td>
</tr>
<tr>
<td>Coefficient of training</td>
<td>$\eta$</td>
<td>0.02</td>
</tr>
</tbody>
</table>

### Table IV. Activation function.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>The activation function at the hidden nodes</td>
<td>$f_1$</td>
<td>Sigmoid tan</td>
</tr>
<tr>
<td>The activation function at the output nodes</td>
<td>$f_2$</td>
<td>Sigmoid tan</td>
</tr>
</tbody>
</table>

Copyright © 2013 John Wiley & Sons, Ltd.

DOI: 10.1002/dac
In this section, the objectives are to minimize the maximum SLL and perform steering for isotropic linear antenna arrays by controlling different parameters of the array elements (amplitude and phase).

The training phase is illustrated in Figure 9. It represents the evolution of the mean square error between exits of the NN and samples given according to the number of epochs, the gotten final error is $9.99988 \times 10^{-7}$.

4. THE NOVEL DESIGN OF PHASED ANTENNA ARRAY

In this section, a description of the system model used in the simulation and the analytical study is presented. The model includes neural model, digital beamforming, phased shifter, antenna array.
4.1. Phased antenna array

We present in this section an electronic platform dedicated to the implementation of a phased antenna array.

After having developed the model of control for the 10 digital phase shifters (eight bits), in the following, we proceed to the implementation for synthesizing phases by the Taguchi algorithm. Our solution is to divide the space into 15 sectors (S1,..., S15), repeated every 10° in the interval from −75° to +75° inclusive; each sector represents a steering lobe. The update of the synthesized weights is carried out at the rate of the movement of the source that indicates the choice of the sector. We find a selection input (Sector lobe), which presents the return of source localization algorithm (MUSIC, ESPRIT…), which indicates the angular position of the user. Once the pointing angle is given, the control device generates the outputs (synthesized phases), which will be the inputs for the digital phase shifters. In practice, many array problems cannot consider the use of variable attenuators, mainly because of losses, space availability, and cost, as well as other design constrains, so the excitations applied to the radiating elements are required to have constant amplitude, being the phase the only variable parameter. Figure 10 gives idea about
principle of the adaptive array technique, which the adaptive array can track the signals, and allocates beams in the direction of the of use signal while simultaneously nulling unwanted sources interference [21–24].

4.2. Results and measurements

The measurement setup in a radio anechoic chamber is shown in Figure 11. The prototype in the developed tested system includes the RF Generator Lab (Laval University, Quebec, Canada), antenna array, phase shifter, and beamformer circuits. Further, it controls all measurement instruments for transceiver. The transmitting signals at an intermediate frequency band of 1 kHz are generated by the synthesized sweeper 83642A (2–40 GHz). At the receiver, a four-element uniform linear array of sleeve antennas equi-spaced by λ/2 was employed. The antenna array was tested at 2 GHz. In both cases, a power divider was connected in order to achieve the array return loss.

The power dividers used are as follows:
- Anaren 44010 1–4 GHz
- RF Generator Lab Volt 1–10 GHz (1 kHz, transmission signal)
- Yagi antenna 1 GHz (Figure 11(b))
- Phase shifter (Figure 12(a))
Experiments were conducted in a radio anechoic chamber to test the basic performance of the proposed approach. An antenna system developed for application to communications was used in the experiment. An antenna array with four 4-element was built for 2GHz operation and is shown in Figure 11. This array has a fixed elevation beam pattern (E-plane) shown in Figure 11(a), and can be synthetically steered in the azimuth plane (H-plane). The sub-array spacing is set to 7.5 cm, which is 0.5\(\lambda\) at 2 GHz for suppressing grating lobes over the scanning angle from 0° to 360°. These antennas are excited by Taguchi-NNs synthesis phases [24].

4.3. Mutual coupling

The geometry used in the calculation of the mutual coupling between two identical antennas is shown in Figure 12. In order to obtain an expression for the mutual coupling, we model the two antennas as a general two-port network, where the mutual impedance is written as

\[
Z_{12} = \frac{V_1}{I_2} \bigg|_{I_1 = 0}
\]

Once the mutual impedance has been obtained, the \(S_{12}\) scattering parameter is calculated using

\[
|S_{12}|_{\text{dB}} = 20\log_{10} \left| \frac{2Z_0Z_{12}}{(Z_{11} + Z_0)^2 - Z_{12}^2} \right|
\]
Figure 13. Simulation and measured radiation patterns of four antenna arrays at 90°F = 2 GHz. (a) Azimuth plane. (b) Elevation plane.

Figure 14. Simulation and measured radiation patterns of four antenna arrays 150°F = 2 GHz. (a) Azimuth plane. (b) Elevation plane.

Figure 15. Simulation and measured radiation patterns of four antenna arrays 210°F = 2 GHz. (a) Azimuth plane. (b) Elevation plane.
Where we typically assume $Z_{11} = Z_0 = 50\Omega$. For the remainder of this work, we will refer to it as the coupling magnitude.

To illustrate the performance of the method described in the earlier section for steering single beam in desired direction by controlling the amplitude and phase excitation of each array element, three examples of linear antenna array with $N = 4$, one-half wavelength spaced isotropic elements were performed [20].

The results of steering beam in the direction of the desired signal are presented in Figures 13–15. These figures show the measured radiation patterns in E-plane and H-plane in different pointing angles at $90^\circ$, $150^\circ$, and $210^\circ$ (Table V).

Measured radiation patterns show excellent agreement with theoretical prediction in both E-plane and H-plane. Electrical features of the array remain stable through the whole frequency range.

There are good agreements between the Taguchi-NNs synthesis weight and measurement in azimuth/elevation and E-plane/H-plane, respectively. From these results, we can predict synthesis weight. Finally, this method presents a good beam scanning performance when the gain variation is below 3 dB within the beam scanning volume between $0^\circ$ and $360^\circ$.

5. CONCLUSION

This paper introduces a novel electromagnetic optimization technique using Taguchi’s method with NNs. The concept of orthogonal arrays and Taguchi-NNs optimization method were described in this paper. The global optimization technique based on Taguchi’s method was applied on the design of linear antenna arrays. The advantage of Taguchi’s optimization technique is the ability of solving problems with a high degree of complexity using small number of experiments in the optimization process. Taguchi’s method is easy to implement and converges to the desired goal quickly. To demonstrate this technique, a linear antenna array is optimized to realize a null control pattern and a sector beam pattern. It is found that Taguchi’s method is simple to implement, and it converges to the desired patterns quickly. This method is an excellent candidate for optimizing electromagnetic (EM) applications.

ACKNOWLEDGEMENT

This work was supported by the Laval University.

REFERENCES

10. Weng C, Choi T. Optimization comparison between Taguchi’s method and PSO by design of a CPW slot antenna Antennas and Propagation Society International Symposium, APSURSI ’09, June 2009

**AUTHORS’ BIOGRAPHIES**

**Amor Smida** received the degree in Electronic Baccalaureate in 2008 and the Master of Science degree in Analyze and Digital Processing of the Electronic Systems in 2010. From 2009 to present, he was a graduate student researcher with the Unit of Research in High Frequency Electronic Circuits and Systems. Since August 2010, he has been a contractual assistant in the Computer and Communication Department at Higher Institute of Applicator Science and Technology of Gafsa, Tunisia. His current research focuses on smart antennas, Taguchi’s method, neural network applications in antennas, adaptive arrays, and microwave circuits design central standard time studio microwave.
Ridha Ghayoula received the Diploma Engineer degree in Automatic-Electrical in 2002 and the Master of Science degree in Analyze and Digital Processing of the Electronic Systems in 2005 and the Doctor of Philosophy degree in 2008 from Tunis El Manar University, Faculty of Mathematical, Physical and Natural Sciences of Tunis, Tunisia. From 2004 to 2012, he was a graduate student researcher with the Unit of Research in High Frequency Electronic Circuits and Systems. Since August 2009, he has been an assistant professor in the Electrical Engineering Department at Higher Institute of Computer Science of El Manar, Tunisia. Since May 2012, he has been a student researcher in Radiocommunications and Signal Processing Laboratory (LRTS), Department of Electrical and Computer Engineering, Laval University, Québec Canada. His current research focuses on software engineering, field programmable gate array, soft-core processor, modeling and simulation, time difference of arrival, direction of arrival, phased arrays, smart antennas, direction finding, radio-communication systems, neural network applications in antennas, adaptive arrays, and microwave circuits design. Dr. Ghayoula has published more than 42 journal and conference papers on smart antennas.

Nadhem Nemri received the degree in Electronic and Informatic Baccalaureate in 2009 and the Master of Science degree in Analyze and Digital Processing of the Electronic Systems in 2011. From 2010 to present, he was a graduate student researcher in the Unit of Research in High Frequency Electronic Circuits and Systems. Since Septembre 2011, he has been a contractual assistant in software engineering and information system department at Higher Institute of Computer Science of El Manar, Tunisia. His current research focuses on smart antennas, Taguchi’s method, neural network applications in antennas, adaptive arrays, and difference of arrival, direction of arrival, phased arrays, direction finding.

Hichem Trabelsi was born in Tunisia in 1962. He received the PH.D. degree in electronics from the University of Pierre & Marie Curie, Paris VI, France in 1991. He joined the department of Physics at the Faculty of Sciences, Tunis, in 1992, where he is currently working on microwave active and passive filters and electromagnetic theory for solving field problems in microwave circuits.

Ali Gharsallah received the Radio Frequency Engineering degree from the Higher School of Telecommunication of Tunis, Tunis, Tunisia, in 1986, and the Doctor of Philosophy degree from the Engineering School of Tunis, Tunis, Tunisia, in 1994. Since 1991, he has been with the Faculté des Sciences de Tunis, Department of Physics, University El Manar Faculty of Sciences of Tunis, Tunis, Tunisia. He is also a full professor of Electrical Engineering and director of Engineering with the Higher Ministry Education of Tunisia, Tunis, Tunisia. He has authored or coauthored approximately 70 papers published in scientific journals and 120 conference papers. He has also supervised over 20 theses and 50 masters. His current research interests include smart antennas, array signal processing, multilayered structures, and microwave integrated circuits.
Dominic Grenier received the Master of Science and Doctor of Philosophy degrees in Electrical Engineering in 1985 and 1989, respectively, from the Université Laval, Quebec City, Canada. From 1989 to 1990, he was a postdoctoral fellow in the Radar Division of the Defense Research Establishment in Ottawa, Canada. In 1990, he joined the Department of Electrical Engineering at Université Laval where he is currently a full professor since 2000. He was also coeditor for the Canadian Journal on Electrical and Computer Engineering for 6 years. His research interests include inverse synthetic aperture radar imaging, signal array processing for high resolution direction of arrivals, information fusion for identification, and reflectometry probes design and signal processing. He has many collaborations with the Development and Research for Defence Canada Center, and with industries under grants or contracts. He was recognized by the undergraduate students in Electrical and Computer Engineering at Université Laval as the electromagnetism and radio frequency (RF) specialist. His excellence in teaching has resulted in ‘Best Teacher Award’ directly from student’s associations many times, the sum of Science and Engineering (SUMMA)-teaching award from Engineering Faculty and the Excellence-Teaching Award from Université Laval in 2010; finally, he received a special teaching recognition award in 2012 from ‘Ordre des ingénieurs du Québec’. He obtained in 2009 one special fellowship for teaching from the Quebec Minister for Education. Prof. Grenier has 39 publications in refereed journals and 75 more in conference proceedings. In addition, more than 40 graduate students completed their thesis under his direction since 1992.