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T/R Module failure correction in active phased array antenna system

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ABSTRACT

This paper presents particle swarm optimization (PSO) technique to mitigate the radiation performance of an active phased array antenna under the condition that a selective number of radiating elements have malfunctioned. The PSO algorithm has been applied to determine the excitation coefficients of array elements yielding optimum performance of an active phased array antenna with a few elements which have failed. Simulated radiation performance has been presented for different cases of failure.

KEYWORDS

Particle Swarm Optimization (PSO);
Transmit/Receive (T/R) Module;
Synthetic aperture radar;
Genetic algorithm;
Personal best (pbest);
Global best (gbest).

INTRODUCTION

Active phased array antennas are widely used in multimode Synthetic Aperture Radar (SAR), Satellite Communications, multi object tracking radar etc as a reliable antenna system for electronic beam scanning. Active phased array antenna system comprises of array of radiating elements having variable phase and amplitude excitation co-efficient controls at each element or at sub-array level for pattern shaping as well as to electronically scan beams to specified angles in space. In order to control the phase and amplitude of each radiating elements/sub-arrays, RF Transmit/Receive (T/R) modules are attached to the elements/sub-arrays. With these components, the transmitting/receiving antennas can electronically scan two independent beams or a specified beam. The active phased array antenna system of high gain and high beam agility requirement has large number of radiating elements and thus the probability of failure of T/R modules as well as malfunctioning of the radiating elements are high [1]. Replacing the faulty T/R modules or antenna elements may not be possible in many systems where the access to the array is not feasible especially in the case of a space-borne phased array antenna system. T/R module failures can severely distort the far-field pattern of array antennas designed for very low side-lobe and cross-polarization characteristics.

Active phased array antenna system offers a very good flexible and reliable design as the array performs with graceful degradation even when the T/R modules of some of the elements failed. In the case when the number of failures at elemental levels is not very high and the radiation performance has not degraded very seriously, the pattern shape and side-lobe level may be recovered by re-distributing the excitation co-efficient. Thus it is worthwhile to explore suitable techniques to compensate T/R module failures.

Very few methods have been reported for array element failure correction in the open literature. Peters[10] has proposed a method to reconfigure the amplitude and phase distribution of the non-failing elements by minimizing the average SLL, via a conjugate gradient method. This method was applied to the synthesis of sum and difference patterns of planar arrays with failed elements. Yeo et al.[3] have described an approach based on Genetic Algorithm (GA) for array failure correction of arbitrary digital beamforming arrays. Yang and Stark[11] reported the method of vector space projections for the recovery of a reasonable antenna performance when as many as 30% of the elements had failed. Mailloux[9] has used the method of replacing the signals from failed elements in a digital beamforming receiving array. All this methods were applied to small array. In case of high gain planar array with a large number of radiating elements, the rate of convergence using the above techniques may be too slow to arrive at an optimum solution. In case of GA, the convergence is slow because of large cross-over and mutation between all populations for a high-gain array antenna. Hence, for real-time applications, GA may not be preferred. Boeringer[4] has described a new approach based on the Particle Swarm Optimization (PSO) technique for phased array antenna which is relatively simpler, faster and at the same time yields accurate results. PSO is a stochastic evolutionary computation technique, based on movement and intelligence of swarms[4-10].

In this paper, the analysis of planar active phased array antenna in which T/R modules are fed at linear array level is carried out considering different number and locations of faulty T/R modules. This type of active phased array antenna finds applications in SAR system where the scanning of beam is done only in one direction. The degradation in array performance caused by the faulty T/R modules have been mitigated by re-distribution of the excitation co-efficients of the remaining radiating elements/sub-arrays in which the T/R modules perform satisfactorily. The optimization of the radiation performance has been carried out using PSO algorithm. Using this analysis, it has been demonstrated the failure cases as a function of locations and the number of T/R modules that have failed and the extent of recovery of radiation pattern. This information may be used to judge the graceful degradation of the active phased array antenna system in case of multiple failures of T/R modules.

PROBLEM FORMULATION

In order to demonstrate the fault analysis as well as its mitigation, the active phased array planar antenna of 24x16 radiating elements at C-band (5.3GHz, centre frequency) has been considered. The radiating elements have been chosen as planar microstrip patch antennas and the elemental spacing across the rows and columns has been taken as $d_x = d_y = 0.7\lambda$. In total 16 T/R modules are connected to the 16 rows of printed microstrip patch antenna elements. The schematic of the antenna is shown in Figure 1.

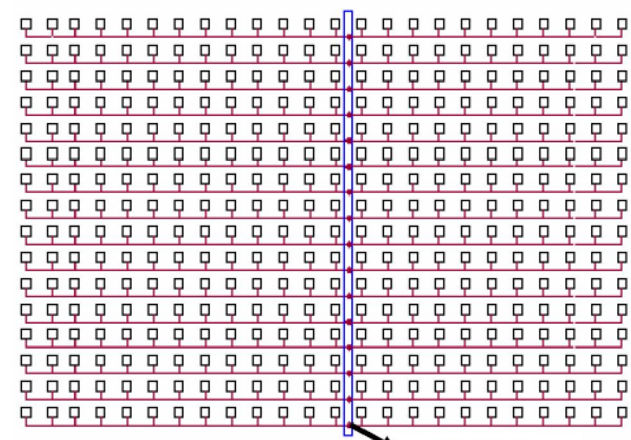

Figure 1 : Planar array antenna of 24x16 radiating elements with 16 T/R module fed at each row

The far field pattern of this rectangular planar phased antenna with MxN = 24x16 radiating elements arranged along a rectangular grid and spaced by d_x in the x direction and by d_y in the y direction, can be written as the product of the element pattern (EP) and the array factor (AF)

$$F(u,v) = EP(u,v) * AF(u,v) \quad (1)$$

$$AF(u,v) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} A_{mn} e^{jk(md_x u + nd_y v)} \quad (2)$$

Where,

$$u = \sin\theta\cos\phi$$
$$v = \sin\theta\sin\phi \quad (3)$$

A_{mn} – Complex excitation of the (m, n)th element; k – Wave number in free space

In the event of one T/R module fails, the excitation co-efficients of all the elements the linear array which is fed by this T/R module is assumed to be zero. Thereafter, PSO technique is applied to correct the SLL and the main beam shape of the pattern to recover as close as to pre-failure specifications. The acceptable value of the SLL after correction has been taken as taken as –13.26 dB. The analysis results given in the next sections deal with the failure cases by considering uniform excitation of all the elements when there are no failed T/R modules and all the elements are active. Different cases of failure have been considered systematically by assuming the T/R modules connected to different linear arrays are not functioning.

DEVELOPMENT OF PSO TECHNIQUE FOR FAILURE CORRECTION

The iterative formula of standard PSO algorithm for an N-dimensional problem is given as follows[7],

$$A(n+1) = (w \times A_n) + (c_1 \times rand_1 \times (pbest_n - A_n)) + (c_2 \times rand_2 \times (gbest_n - A_n)) \quad \textbf{(4)}$$

This equation (4) is used for updating current excitations of radiating elements in array antenna. The superscripts n+1 and n refer to the time index of the current and the previous iterations. $P_{best,n}$ is the personal best position which defines best side lobe level of each individual population. $g_{best,n}$ is the global best position which defines the optimum side lobe level for all population. The $rand_1()$ and $rand_2()$ are two uniformly distributed random numbers in the interval in between 0 and 1. The parameters c_1 and c_2 specify the relative weight of the personal best position versus the global best position. Eberhart et al. have concluded that a value of 2.0 is a good choice for both the parameters[9]. Recent parametric studies have suggested, however, that the optimal choice for c_1 and c_2 is 1.49[6]. The parameter ω is a number, called the "inertial weight," in the range between 0 and 1, and it specifies the weight by which the particle's current excitations depends on its previous excitations and how far the particle is from its personal best and global best positions. Robinson and Rahmat-Samii[6] have concluded that the PSO algorithm converges faster if ω is linearly damped with iterations starting at 0.9 and decreasing linearly to 0.4 at the last iteration using the following equation.

$$w = w_{\max} - \left(\frac{(w_{\max} - w_{\min})}{Max.\ Iteration} \right) \bullet (IterationNumber) \quad \textbf{(5)}$$

The implementation of PSO algorithm for active phase array antenna tile of 24x16 elements is described below.

Initialize parameters

The number of population (solution space) is related to convergence speed of algorithm. In the current implementation of the particle swarm optimizer, population size should be less than 30[6]. An initial population of at least 5 random populations is generated. The weighting vectors of the degraded array pattern are added to replace one of the weakest individuals among the initial population. Their insertion helps to improve the rate of convergence[3].

MATLAB command that yields a random population matrix of *npop* chromosomes is given by

$$\begin{aligned} population &= rand\,(npop - 1,\ nelem) \\ newpop &= [population;\ failarrayexc] \end{aligned} \quad \textbf{(6)}$$

Fitness unction

The fitness function and the solution space must be specifically developed for each optimization; the rest of the implementation, however, is independent of the physical system being optimized. As discussed, due to elements failure in active phase array antenna, SLL raises which is required to minimize. Thus the SLL of an antenna will become fitness function of the algorithm. Now due to consideration of SLL only for fitness function; when number of iteration increases, main beam becomes more and more broad. Hence, in fitness function, other considerations are array factor of original pattern (without failure) and corrected pattern. So fitness function becomes,

$$f = \sqrt{\left(\frac{AFd - AFc}{AFd}\right)} - \sqrt{(SLLd) - (SLLc)} \quad \textbf{(7)}$$

AF_d– Desired Array Factor without failure; AF_c– Corrected pattern Array Factor; SLL_d– Desired SLL; SLL_c–SLL of antenna array with failed elements

$$error\ function = \frac{(Fitness\ Function)_d - (Fitness\ Function)_c}{(Fitness\ Function)_d} \quad \textbf{(8)}$$

A template, formed by the shape of the main lobe and the specified SLL, is cast over the array pattern produced by each population to compute their difference as a form of fitness measure in decibels. Thus the ideal array pattern is one that conforms to the original main beam shape with the specified SLL. Hence correction algorithm must be tried to minimize this error function of equation (8).

Initialize pbest and gbest

In order to begin searching for the optimal position in the solution space, each particle begins at its own random current amplitude excitations. Since its initial position is the only location encountered by each particle at start of runs, this position becomes each particle's respective *pbest*. It means that individual particle side lobe level becomes each particle's personal best value. The first *gbest* is then selected from among these initial excitations.

Update the particle's excitation

The manipulation of a particle's excitations is the core element of the entire optimization. The excitations of the particle are changed according to the relative locations of *pbest* and *gbest*. It is accelerated in the directions of these locations of greatest fitness according to the equation (4).

Evaluate the particle's fitness, compare to gbest pbest

The new excitations of the particle are calculated by adding the new excitation vector to the old particle excitation vector as indicated in equation (4). This new position is then mapped to amplitude weights and the new resulting far-field pattern is scored. If this position has the best score that this particle has found so far, then it is retained as the local best memory for this particle. If in addition, this position has the best score of any particle so far, then it is further retained as the global best for the entire swarm. The final array distribution is taken as the global best scoring particle after a specified number of iterations are reached. The current implementation of the particle swarm optimizer uses asynchronous updates[2], where the global best is updated after each particle, rather than waiting until all the particles have been scored. This makes the most current global best information known to all particles as soon as it becomes available.

Repeat

After this process is carried out for each particle in the swarm, the process is repeated starting at step of B. Repetition of this cycle is continued until the termination criteria are met.

There are several methods to determine these termination criteria. The most often criterion used in optimizations with PSO is a maximum iteration number. With this termination condition, the PSO ends when the process (starting with step 3.4) has been repeated a user-defined number of times. Other criterion is a target fitness termination condition, i.e. set minimum fitness function value. With this option the PSO is run for the user-defined number of iterations, but at any time if a solution is found greater than or equal to the target fitness value, the PSO will stop. This is useful when one has a very specific engineering goal for the value of the fitness function, and is not necessarily concerned with finding the "best" solution. In some cases if a solution is found to be better than the target fitness, then the solution is good enough and there is no reason to continue the run.

SIMULATION RESULTS & DISCUSSIONS

In this section representative numerical results of failure in active phased array antenna as described in section 3 are presented. The excitation co-efficients of the planar array antenna of 24x16 microstrip radiating elements spaced uniformly 0.7λ apart computed for a side-lobe level of – 13.26 dB using uniform array synthesis technique are used as initial value to predict the radiation pattern termed as ideal pattern considering all elements are active.

The algorithm has been implemented with following system specifications; MATLAB 7.5 simulation tool, windows XP platform, 2.13 GHz core2duo P-IV processor with 1GB RAM. The following cases of failure have been considered.

Failure of one row: 9th row

In this case, 9th row from the top as shown in Figure 1 is considered to be failed because of the failure of T/R module attached to it. Let us consider the beam $\theta_0 = 90^o$ and $\varphi_0 = 0^o$ where an entire 9th row of the planar structure fails. After this row fails, far field pattern is shown using dashed line in Figure 2. The SLL raises from – 13.26 dB of uniform array to – 12.33 dB. After applying PSO algorithm for parameters; a size of swarm

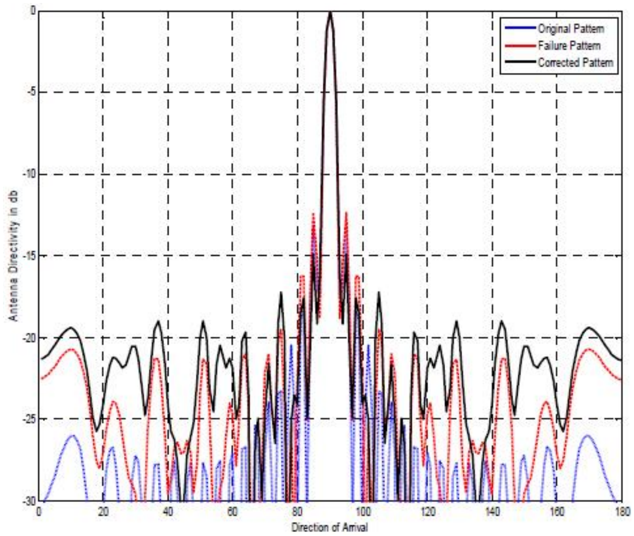

Figure 2 : Corrected pattern along with original pattern and uncorrected pattern with main beam pointing at broadside considering the 9th row T/R module failure

set to 5 particles. The maximum numbers of iteration are 10 and the required minimum SLL is set to –13.26 dB, without failure SLL requirement. The SLL –14.8936 dB can be achieved with single iteration of PSO technique. The computational time will be hardly 0.70 second.

Failure of central row: 12th row

For the same configuration of array antenna as mentioned above, now let us consider the T/R module of the central row fails and in this case entire radiating elements of centre row fails. After this elements fail, SLL raises from – 13.26 dB to – 11.36 dB of uniform

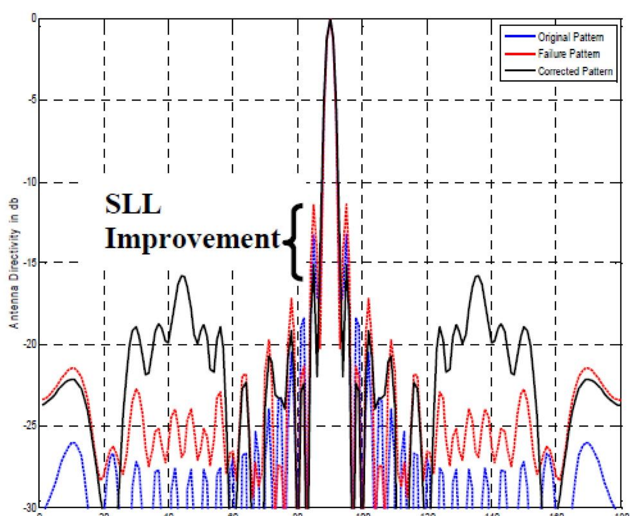

Figure 3 : Corrected pattern with main beam pointing at broadside and failures at central row with original and un-corrected pattern

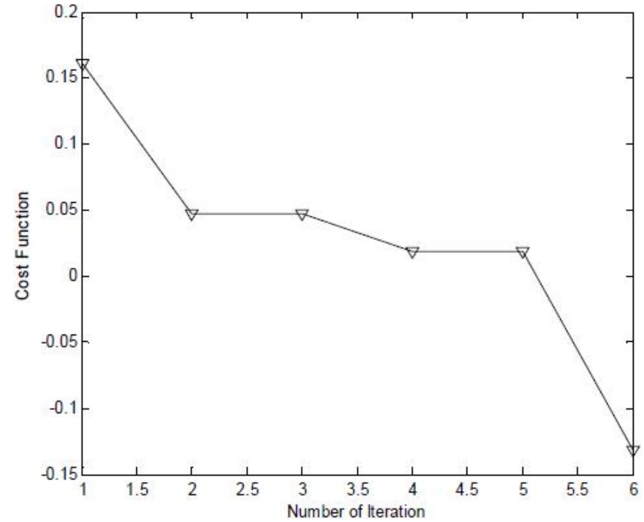

Figure 4 : Fitness progress curves, obtained of 6 iterations, with main beam directed at broadside and elements of centre row failures

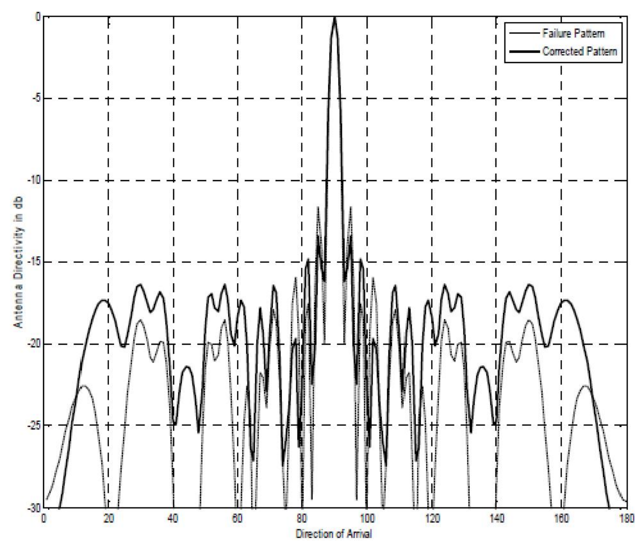

Figure 5 : Corrected pattern when elements of entire 7th and 12th row failures with uncorrected pattern

array. In this kind of failure, GA technique for failure correction does not work[3]. PSO algorithm is applied for the same parameters as mentioned in previous case but more iteration will be required to achieve the converged value of side lobe level. Here six numbers of iterations have yielded the converged result. After correction, SLL of far field pattern – 15.0859 dB as shown in Figure 3. The fitness progress curve, obtained over 6 iterations, is illustrated in Figure 4.

Multiple row failure correction

Let us consider the case when entire two and three row fails in 24x16 rectangular planar array structures.

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If two and three T/R fails 80% and 70% T/R modules are properly working. Let us examine the case of 7th and 12th row T/R modules fail, side lobe level raises – 11.60 dB and after failure correction using same parameter corrected far field pattern is shown in Figure 5.

After correction, SLL of far field pattern -13.3717 dB as shown in Figure 5. This is made possible by the insertion of the solution for the above single row elements failure correction, else more generations will be required to achieved satisfactory fitness level. Further consider entire three rows 7th, 12th and 20th elements T/R module fails and after corrected pattern using PSO is shown in

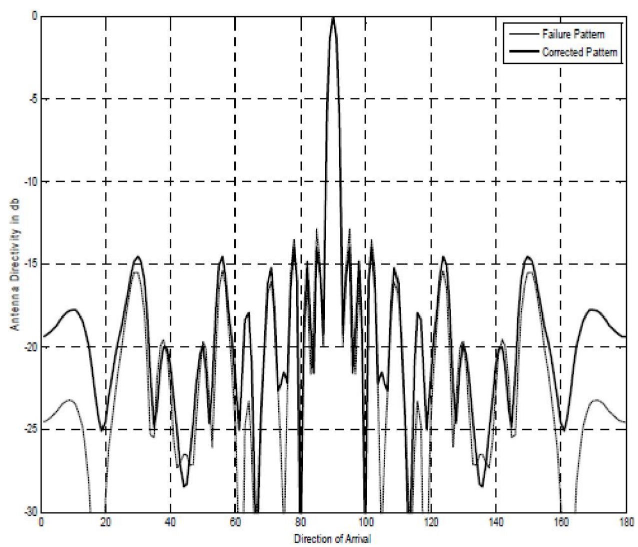

Figure 6 : Corrected pattern when elements of entire 7th, 2th and 20th row failures

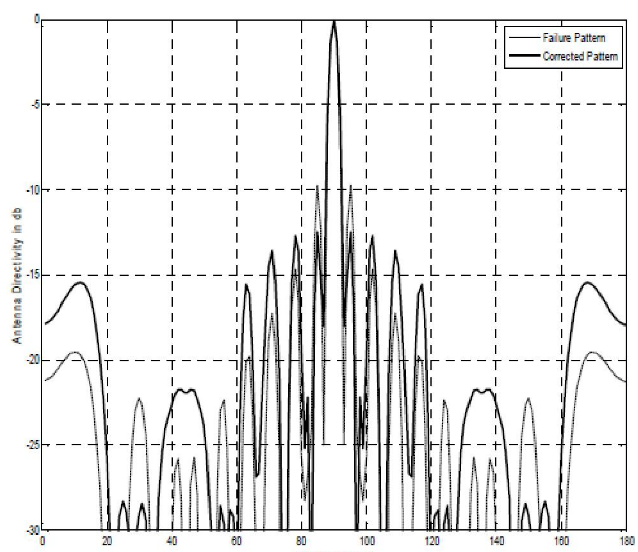

Figure 7 : Corrected pattern when elements of entire 12th and 13th row failures

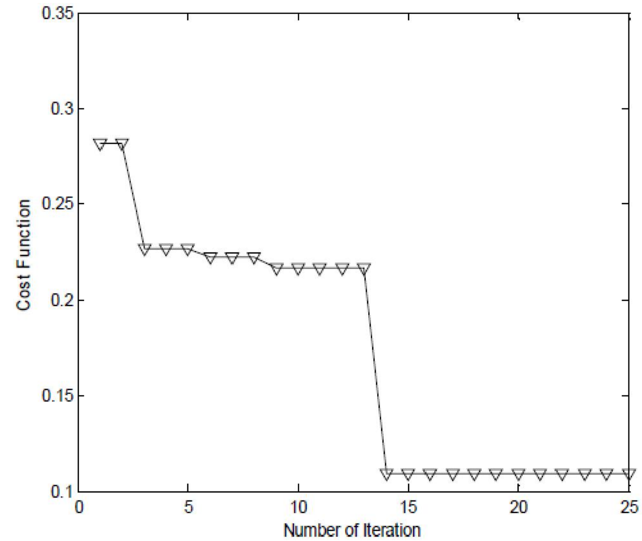

Figure 8 : Fitness progress curves, obtained of 25 iterations, with main beam directed at broadside and elements of two centre row failures

Figure 6.

Improvement of side lobe level is 1.1106 dB, due to failure SLL – 12.8443 dB and after correction SLL – 13.9549 dB.

Finally consider the case of two centre rows 12th and 13th fails, after PSO run simulation results are shown in Figure 7 and Figure 8. In this figure, we clearly observed that two centre rows failure than so much degradation in SLL. The correction algorithm minimizes error function up to 0.115 within 25 numbers of iteration.

CONCLUSION

PSO technique has been applied to array failure correction of single-, double-, and three row failures. The PSO algorithm is used to optimize the excitation amplitude of array elements to realize the array pattern with improved side lobe level as compared to the degraded pattern because of T/R module failure. The success of correcting a damaged pattern depends heavily on the original excitation of the failed element and the number of failed elements. In this instance, if the entire 12th and 13th element fails resulting in a blockage, it would be impossible to correct or yield any improvement. Incidentally, for more than two number of row failures at position 2nd, 7th and 20th, it is easier to recover as compared to those with failed row position at centre. The particle swarm optimization technique demonstrates the possibility of its application for recovery system in real time application. As PSO optimize SLL using less number of iteration without crossover and mutation unlike in genetic algorithm so it has lesser computational cost. Hence, the proposed particle swarm optimization technique for element failure correction in active phased array antenna can be used to solve many practical problems with faster convergence by maintaining required side lobe level.

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