Pareto optimisation of a switched parasitic array antenna

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***Abstract*—This paper examines the approximation trade-off surface of an parasitic array antenna in terms of the radial size of the array and radiation lobe gain using three multi-objective optimisation algorithms.**

***Index Terms*—Pareto optimisation, antenna array.**

I. Introduction

Antenna systems providing a directional radiation lobe have many advantages in wireless communication links. In particular, it assists in the minimisation of multi-path fading effects. Using directed electromagnetic radiation the potential increase in system gain and range of the communication link is considerable with no additional relay stations or higher signal power required. In most applications of wireless communications and computing the network topology will be ad-hoc. This requires the antenna system to be both directional and adaptive according to the ambient surroundings. Devising an antenna technology that allows for this and is commercially viable is an active research topic. Several smart antenna technologies have been proposed in recent years however, the parasitic array is perhaps the most widely researched technology. They offer a simple and cost effective form of adaptive antenna technology.

This paper presents the design of a 7-element switched parasitic array featuring monopole elements embedded in a dielectric material to facilitate size reduction [1]. From a commercial perspective, physical size and horizontal gain are the most significant factors to considers. It is well known that in electrically small antennas, gain and size are inversely correlated parameters. If the gain of the antenna is optimised solely and the antenna size a design parameter, theoretically one would expect the algorithm to converge towards a solution with the largest size allowed. To prevent this we propose the use of so-called multi-objective optimisation using *a posteriori* preference articulation towards the size and gain of the antenna. This allows us to approximate all possible compromise solutions.

II. Switched Parasitic Array Antenna

Figure 1 shows the proposed 7-element array with the parasitic monopole elements in a circular configuration spaced 60° apart. The active monopole element is located in the centre of the array. A hollow cylindrical ground skit is used to reduce the lateral size of the ground-plane. Due to the symmetrical nature of the array, any directional radiation lobe formed can be rotated throughout the azimuth by manipulating the states of the parasitic elements.

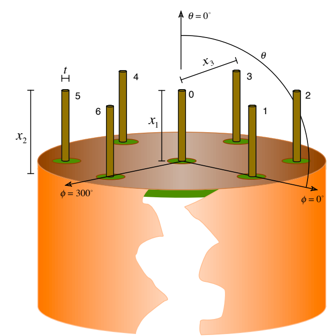

Fig. 1: Illustration of the 7-Element dielectric embedded (omitted) switched parasitic array.

III. Multi-Objective Optimisation

A multi-objective optimsation problem is the search for a minima or maxima for a set of functions that all share the same variables. That is, assuming a minimisation problem, find $\mathbf{x} = \{x_1, x_2, ..., x_n\}$ to minimise $\mathbf{F}(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x}), ..., f_m(\mathbf{x})\}$. In *a posteriori* preference articulation, this involves application of the Pareto dominance condition defined as:

A decision vector, $\mathbf{x}_1$, is said to dominate decision vector, $\mathbf{x}_2$, denoted $\mathbf{x}_1 \prec \mathbf{x}_2$, if:

- $\mathbf{x}_1$ is not worse then $\mathbf{x}_2$ for all objectives, $f_i(\mathbf{x}_1) \leq f_i(\mathbf{x}_2) \quad \forall i = 1, ..., m$ and
- $\mathbf{x}_1$ is strictly better then $\mathbf{x}_2$ for at least one objective $f_i(\mathbf{x}_1) < f_i(\mathbf{x}_2) \quad \exists i = 1, ..., m$

Given the set of all possible solutions $\mathbf{X}$, the set of all Pareto optimal decision vectors form the Pareto optimal set, $\mathbf{P}$. That is:

$$\mathbf{P} = \{\mathbf{x}^* \in \mathbf{X} | \nexists \mathbf{x} \in \mathbf{X} : \mathbf{x} \prec \mathbf{x}^*\} \quad (1)$$

A set of n decision vectors $\mathbf{N} \in \mathbf{X}$ is said to be a *non-dominated set* if no member of $\mathbf{N}$ is dominated by any other member. The Pareto optimal set contains the set of optimal solutions that correspond to the trade-off surface that can be theoretically found. Using this preference articulation, the goal in a multi-objective problem is to find the Pareto optimal set. Of course in a continuous problem a representative subset usually suffices. By definition the Pareto optimal set is a non-dominated set however, a non-dominated set is not necessarily a Pareto optimal set. The objective vectors corresponding to the Pareto optimal set are referred to as the Pareto front.

A. Algorithms

Three different multi-objective optimistion algorithms were employed in this work. These were the well known NSGA-II algorithm [2], a random searching algorithm (RAND), and a developed multi-objective particle swarm optimisation (MOPSO) algorithm. For brevity these algorithms will only be detailed in the full body of work.

IV. Antenna Optimisation

The variables in the optimisation procedure are the height of the active element,height of the parasitic elements, the array radius and the number of parasitic elements short-circuited to the ground-plane. These are denoted as x_1, x_2, x_3 and x_4 respectively. The radius of the dielectric material and ground skirt was set at $4mm + x_3$. The upper $\mathbf{x}^{(U)}$ and lower $\mathbf{x}^{(L)}$ limits of these variables imposed as: $\mathbf{x}^{(L)} = \{10, 11, 16, 1\}$ and $\mathbf{x}^{(U)} = \{20, 21, 26, 5\}$. With a $1mm$ resolution for x_1, x_2 and x_3 6655 possible solutions are produced. Simulating the antenna in Ansoft HFSS$^{\text{TM}}$required 8-25 minutes of computational time depending on the radius of the antenna. Each algorithm performed 1008 evaluations each and this was repeated 25 times to supply a valid sample for statistical analysis.

V. Results

An abstract of the results is given in Figure 2 showing the approximated Pareto front for a particular run immediately suggesting the MOPSO was the better algorithm following by NSGA-II and the RAND algorithms. One of three algorithm metrics used in this work is the error ratio. This ratio is a simple metric suitable for a discrete Pareto front. It quantifies the amount of Pareto optimal solutions missing from the approximated Pareto front. Using the error ratio the quality of the fronts were assessed. The results are presented in a box-and-whisker style plot which readily displays key measures: the enclosed box depicts the lower quartile, median and upper quartile, while the arms extending from the box(whiskers) show the smallest and largest observation of the statistical data. The RAND algorithm has found no more then 30% of the Pareto optimal solutions on it's best run. Worse cases for the NSGA-II and MOPSO algorithm were when 71% and 100% of the Pareto optimal solutions, respectively, were not found. The MOPSO algorithm was the only method to find the true Pareto front.

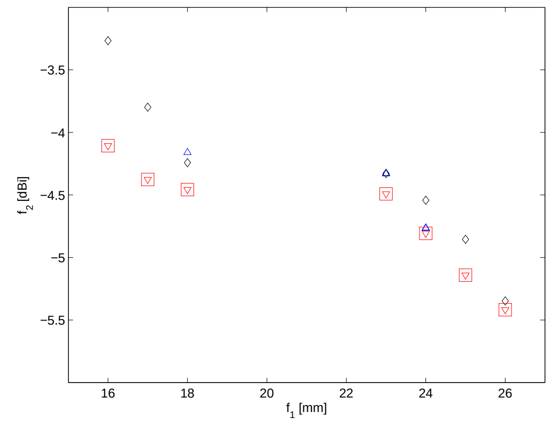

Fig. 2: True Pareto front and approximated Pareto fronts produced by the MOPSO, NSGA-II and RAND algorithms. True Pareto front □ ; MOPSO ▽ ; NSGA-II △; RAND ◇ .

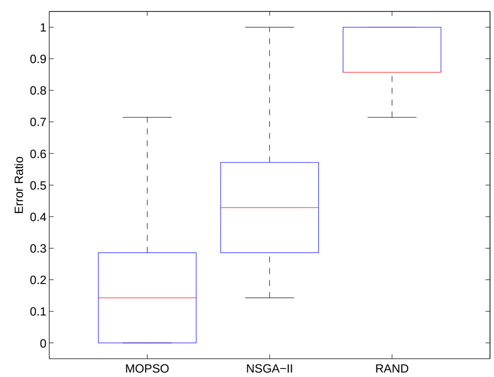

Fig. 3: Box plots of the error ratio metric produced by the MOPSO, NSGA-II and RAND algorithms while optimising the 7-element dielectric embedded switched parasitic array antenna.

VI. Conclusion

This paper has presented the multi-objective optimisation for the design of 7 element dielectric embedded switched parasitic array antenna. Three different algorithms based on the genetic algorithm, particle swarm optimsiation algorithma a random search were employed. The MOPSO algorithm, developed by the authors, was shown to be superior for this problem. The full body of work will a description of the algorithms, more metrics to quantify their performance and analysis on the Pareto-optimal solutions.

References

[1] Junwei Lu, David Ireland and Andrew Lewis, "Multi-objective Optimization in High Frequency Electromagnetics: an Effective Technique for Smart Mobile Antenna" IEEE Transaction On Magnetics, Vol. 45, No. 3, March 2009, pp.1072-107

[2] K. Deb, A. Pratap, S. Agarwal and T. Meyarivan, "A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II", IEEE Transactions on Evolutionary Computation, Vol. 6, pp. 182-197, 2002