CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Context and Background

The modern military radar system postulates the following operational and technological requirements:

- Instantaneous positioning of beam
- Rapid reaction time i.e. high data update rate
- Multi-mode operation
- Multi-target handling capability
- Less mechanical errors
- Higher reliability

These attractive features of radar system gave rise to the development of active antenna array. Even though active antenna arrays would conform to aforesaid appealing radar characteristics, their development necessitates that the antenna array should be of larger size to obtain better angular resolution as well as accuracy.

From another point of view, the inter-element spacing should be of the order of one-half wavelength ($\lambda/2$) at the maximum operating frequency for a maximum practical scan angle of 60^0 in order to avoid the appearance of grating lobes in antenna real space. Conforming to both conditions, viz. fine angular resolution as well as accuracy and avoidance of grating lobes could result in large number of antenna elements on the aperture of the array. Since each antenna element in the active array is associated with an individual source/receiver i.e. transmitting/receiving module (TRM), the cost of a fully dense array for large aperture becomes very high [Ligthart(1985)], and [Coman(2006)]. Additionally, construction of antenna array is subject to mechanical and thermal limitations. Furthermore, since antenna elements on array aperture are positioned close to each other, the mutual coupling would be very dominant. This effect of mutual coupling is often technologically difficult to surmount and causes deleterious change in antenna array performance, particularly in the side lobe level and the scanning capability.

These limitations of cost and mutual coupling can be dealt successfully by reducing the number of antenna elements in the array configuration [Coman (2006)]. If the reduction in the number of array elements is done with escorting increase in the inter-element spacing, the resulting antenna array would be denoted as sparse array (also referred to as space tapered, random, non-uniform, aperiodic or arbitrary array). While the sparse configuration complies by removing antenna elements from a fully dense array, the antenna array is referred to as a thinned array [Coman (2006)]. The gaps between radiating elements of one functionality on array aperture created by escorting increase in the inter-element spacings can be utilized to design and fill with radiating elements for a different functionality, thereby rendering multi-functional antenna arrays sharing the same physical aperture [Ligthart (1985)].

The advantages of utilizing sparse antenna arrays are not limited to cost and mutual coupling. Several other characteristics including bandwidth, weight, power consumption, heat dissipation and multi-functionality are also anticipated to ameliorate, if the average spacing between antenna elements is made greater than $\lambda/2$. The primary drawback of such antenna arrangements is their high level of the peak, average and

RMS side lobe levels in the radiation pattern, which is undesirable in many practical applications especially in radar. Nevertheless, by controlling the number of elements, their locations on the aperture, and their excitation coefficients, it is possible to achieve desired radiation characteristics for most practical applications.

Keeping in view the aforesaid limitations and requirements of active antenna array for radar applications and motivated by the characteristics of sparse antenna arrays, author felt necessary to carry out research in this framework. This research is an emerging field and would help in the further development of technology for military radar antenna systems. The following sparse array configurations are studied in the proposed Ph.D. research work:

- Thinned antenna arrays
- Non-uniformly spaced antenna arrays
- Multi-functional antenna arrays

1.1.1. Thinned Antenna (TA) Arrays

Thinning an array involves the removal (turning off) of some elements from a periodic or uniformly spaced array to create a desired current distribution on the array aperture corresponding to required pattern characteristics [Numazaki *et al.* (1987)]. There are two main advantages of thinned arrays as compared to periodic fully filled arrays. Firstly, the number of radiating elements is considerably reduced which cuts down the cost and weight of the array. Even so, the aperture size is almost maintained, which allows people to get nearly the same resolution of a fully filled array of equal size. Secondly, thinned arrays present the advantage in terms of ease of realization, as different elements usually lie on a regular grid, operate with equal amplitude, and are directly connected to the amplifiers. Owing to the aforesaid aspects, thinned array design has become a hot topic in array synthesis area. Thinned Linear Antenna (TLA) arrays and Thinned Planar Antenna (TPA) arrays as shown in Figs. 1-1 and 1-2 respectively are studied in this part of research work.

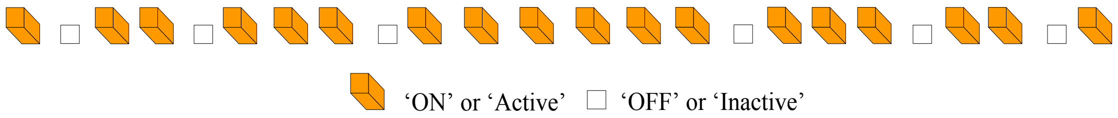

Fig. 1.1: General configuration showing distribution of antenna elements at the aperture of the TLA array.

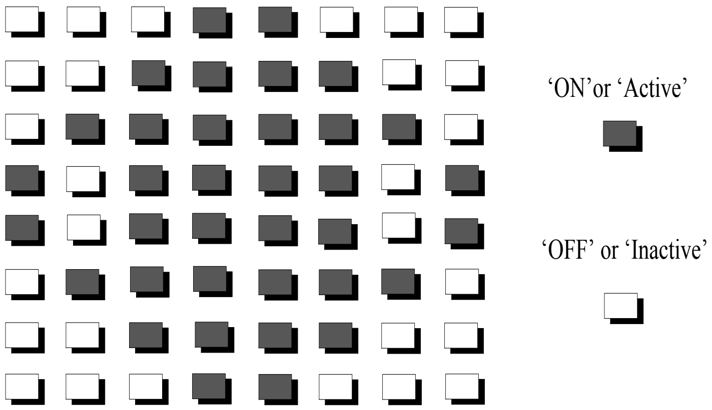

Fig. 1.2: General configuration showing distribution of antenna elements at the aperture of the TPA array.

1.1.2. Non-uniformly Spaced Antenna (NUSA) Arrays

In practical applications, where potential exists to reduce the number of elements, suppressing the side lobe level (SLL), and simplifying the feed network, unequally spaced antenna arrays exhibit distinguishable advantages compared with conventional uniformly spaced arrays. However, due to the nonlinear phase dependence on position, it is difficult to design and analyse unequally spaced arrays to yield the desired radiation pattern.

Aperiodic arrays, as first introduced by Unz [Unz (1960)] are potentially capable of addressing the requirements discussed earlier. To design such arrays, two sparse array approaches are commonly used: one is sparse array with unequal spacing and other is array with random spacing. In both the approaches, a minimum number of elements are optimally positioned according to a specified criterion. Non-uniformly spaced arrays also termed as aperiodic arrays have been studied for several decades. Compared with equally-spaced arrays, aperiodic arrays with optimally spaced sensors can achieve higher spatial resolution or lower side lobes. Such arrays, even with fewer sensors can meet similar pattern specifications by carefully designing the locations of array sensors. Non- uniformly Spaced Linear Antenna (NUSLA) Arrays and Non-uniformly Spaced Planar Antenna (NUSPA) Arrays as shown Figs. 1-3 and 1-4 respectively are studied in this part of research work.

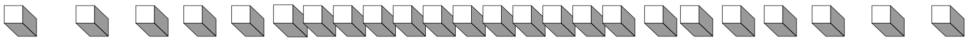

Fig. 1.3: General configuration showing distribution of antenna elements at the aperture of the NUSLA array.

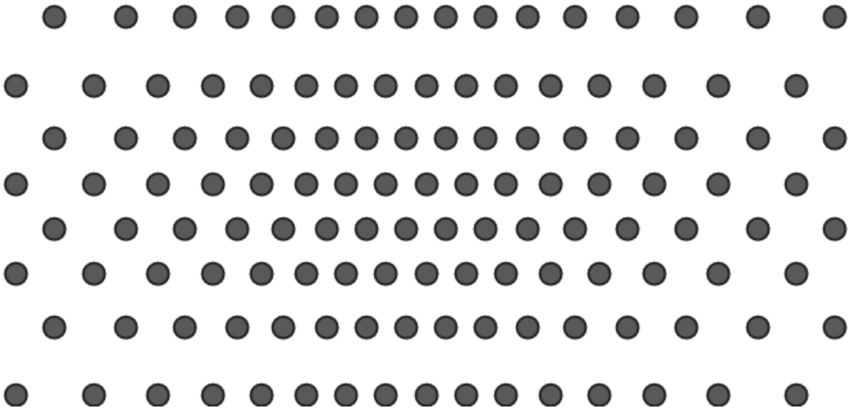

Fig. 1.4: General configuration showing distribution of antenna elements at the aperture of the NUSPA array.

1.1.3. Multi-functional Antenna (MFA) Arrays

The modern radar systems require compact antennas with multi-functional capabilities. There is an urgent requirement to minimize the weight, dimension, DC power consumption and heat dissipation of antenna arrays while at the same instant enforcing several radiation functions within the same physical aperture. This concept is referred to as *multi-functional or shared aperture arrays* [Papapolymerou and Bernhard (2006)]. Additionally, it is also possible to reduce the number of antennas by consolidating the functionality of several antenna systems into a single shared aperture antenna.

Combining the functionality of several antennas into single shared aperture presents several technical challenges as the aperture can be shared between systems in various ways. One method is to use the aperture on time sharing basis judiciously for different functions. Second method is to divide the aperture into sub-apertures and thus use each aperture for specific function as well as use time sharing for some sub-apertures. Using single aperture for multi-functionality poses a design challenge to the antenna engineer, as radiating elements should possess good impedance as well as pattern bandwidth and often multiple polarizations. Also, the array grid for lower frequency applications could suffer from large mutual coupling problem and thereby degrading antenna directivity, and at higher frequencies it could result in early onset of grating lobes by limiting scanning domain to much lesser than desired. The second method of sub-dividing the aperture into individual sub-apertures may not offer full benefits unless some sub-apertures are time-multiplexed. With the help of two NUSPA array configurations operating at different frequencies as shown in Fig. 1-5, the gaps between radiating elements of one NUSPA array can be utilized to design and fill with another NUSPA array for different functionality which gives rise to a multi-functional antenna (MFA) array [Coman et al. (2004)]. The general configuration of MFA array is shown in Fig. 1-5.

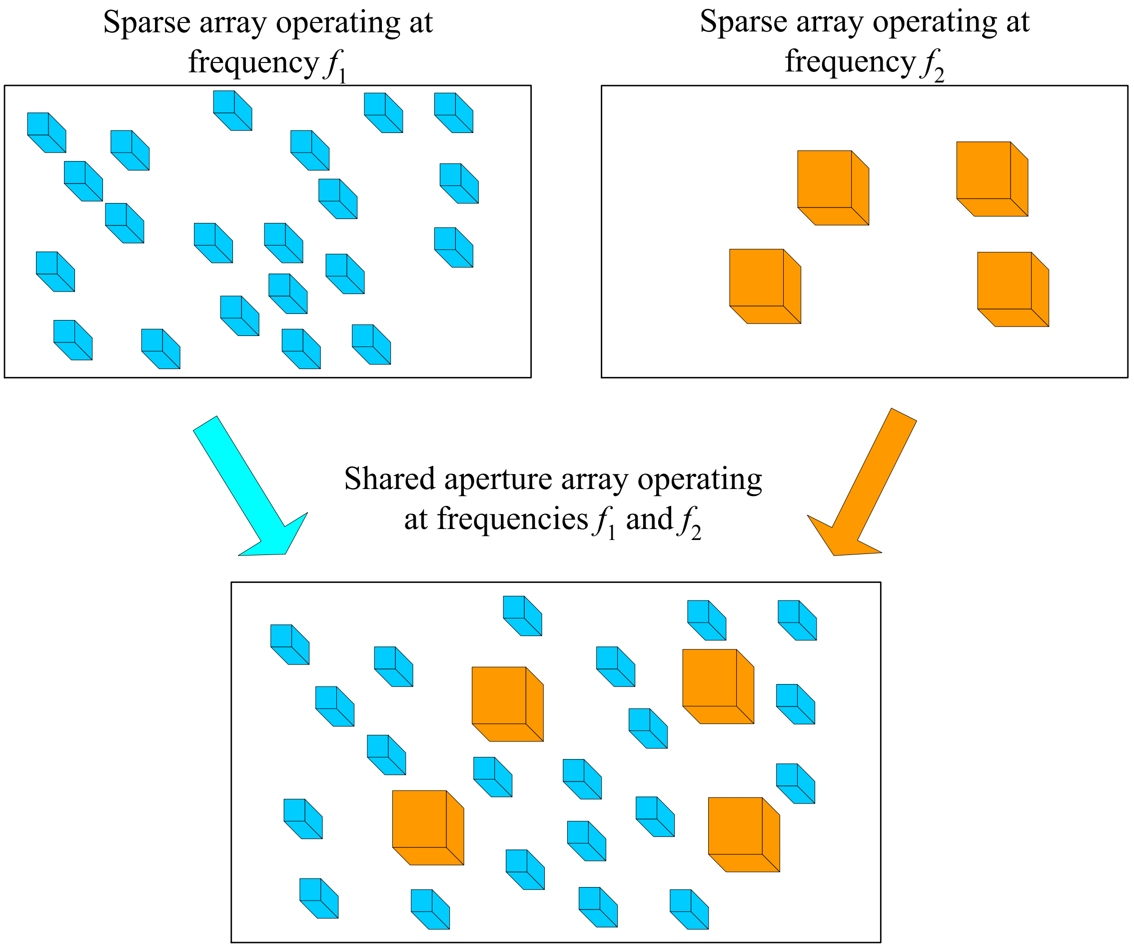

Fig. 1.5: General configuration showing distribution of antenna elements at the aperture of MFA array sharing the same physical aperture.

The MFA arrays based on sparse concept offer the following advantages:

- A sparse array is a non-periodic arrangement of elements with spacing larger than half-lambda and sometimes more than one-lambda. This non-periodic placement inhibits the formation of grating lobes, which could have otherwise existed for a uniform dense array with similar grid spacing.
- To decrease the SLL, aperture distribution must be controlled, which changes the current density over the aperture. This, in turn, controls the pattern characteristics, such as SLL, gain, and beam width. This is called as ‘amplitude tapering’ but it reduces the antenna efficiency. Another way of controlling the current density

over the aperture is by varying the density or distribution of uniformly excited elements. This is called as 'space tapering' and is a primary characteristic of an RSPA array. By optimally choosing the location of elements and by introducing variable density of elements in an RSPA array, lower SLLs (< -13 dB) can be obtained with uniform excitations. But the design and synthesis of MFA array geometry is complex and requires an extensive study.

1.2 Literature Review on Sparse Antenna Arrays

Understanding the work done by other researchers previously in the proposed domain is one of the most vital parts of the present research work. It gives an insight to the subject. Previous research done on the sparse array is discussed below before formulating the proposed study.

The study of non-uniformly spaced linear arrays was for the first time originated with the work of Unz [Unz (1960)], who developed a matrix formulation to attain the distribution of current at the aperture corresponding to desired radiation pattern for an NUSLA array. This study was then continued by many researchers including Harrington [Harrington (1961)], Andreason [Andreason (1962)], Ishimaru [Ishimaru (1962)], king et al. [king *et al.* (1997)], and Kurup et al. [Kurup *et al.* (2003)].

Harrington tried to reduce PSLL down to 2/N times the field intensity of the main lobe, where N is the total number of elements by varying properly the geometrical positions of the array elements [Harrington (1961)].

Ishimaru utilized the Poisson sum expansion to design an unequally spaced uniform amplitude array with any desired PSLL, and did research on the grating lobe suppression [Ishimaru (1962)].

Lo developed a mathematical theory of antenna arrays with randomly spaced elements and studied various probabilistic properties of a large antenna array with randomly spaced elements. He found that for almost all cases of practical interest the required number of elements is closely related to the desired side lobe level and is almost independent of the aperture dimension [Lo (1963)].

Devies and Ward described a new technique for achieving low side lobe directional patterns from thinned arrays. The concept employs multiplicative processing and was therefore restricted to receiving arrays. It was shown that a total of about 3N elements can synthesize a pattern corresponding to a filled array of N^2 elements so that large thinning factors, in excess of 90%, are realizable for large number of elements without degradation of side lobe performance [Davies and Ward (1980)].

Numazaki et al. presented thinning method to realize the desired aperture distribution in a planar antenna array with elements fixed on an array lattice. In this method, elements to be excited were determined by quantizing cumulative weights which are calculated from the desired aperture distribution [Numazaki *et al.* (1987)].

Melloux and Cohen investigated the use of statistical thinning and quantized element weights to produce low side lobe patterns using large circular array apertures. The major result of the analysis is a comparison of several thinning algorithms and the evaluation of side lobe gain and effective radiated power data for large, but otherwise arbitrary size arrays [Melloux and Cohen (1991)].

Haupt presented the method for optimally thinning an array using genetic algorithms. The genetic algorithm determines which elements are turned off in a periodic array to yield the lowest maximum relative side lobe level. Simulation results for 200 element linear arrays and 200 -element planar arrays have been shown. The arrays have been thinned to obtain side lobe levels of less than -20 dB. The linear arrays were also optimized over both scan angle and bandwidth [Haupt (1994)].

Kumar and Branner presented an analytical method based on Legendre transformation to attain optimal current distribution corresponding to desired radiation pattern [Kumar and Branner (1999)].

Trucco proposed a synthesis method that is aimed at designing an aperiodic sparse two-dimensional array to be used with a conventional beam former. The stochastic algorithm of simulated annealing has been utilized to minimize the number of elements necessary to produce a spatial response that meets the given requirements [Trucco (1999)].

Bray *et al.* investigated a method of creating thinned aperiodic linear phased arrays through the application of genetic algorithm that suppressed the grating lobes with increased steering angles. In addition, they demonstrated that the genetic algorithm placed restrictions on the driving-point impedance of each element so that they were well behaved during scanning [Bray *et al.* (2002)].

Liu *et al.* presented the design of non-uniformly spaced linear array suitable for GSM/CDMA base station application. In the design, both the interspacing between array elements and the feeding Wilkinson power divider for tri-band antenna array were facilitated using genetic algorithm [Liu *et al.* (2004)].

Haupt presented three approaches to improve the efficiency of an array aperture by interleaving two arrays in the same aperture area. The interleaved arrays have aperiodic spacings that are integral multiples of a set minimum spacing and were optimized to reduce the maximum side lobe level [Haupt (2005)].

Teruel and Iglesias proposed the ant colony optimization (ACO) as a useful alternative in the thinned array design, using the side lobe level (SLL) as the desirable parameter. They demonstrated that although the work has been focused on thinned arrays where the only parameter is the element state “ON” or “OFF,” there are no restrictions in this method to include other array parameters, such as the amplitude or phase of the elements [Teruel and Iglesias (2006)].

Chen *et al.* proposed an effective approach based on the differential evolution (DE) algorithm for the synthesis of uniformly excited thinned linear phased arrays. Two different measures were introduced in the algorithm for the constraint of the search ranges of the element spacing, and quantized phase excitations were also considered for array feeds with digital devices [Chen *et al.* (2007)].

Mahenti *et al.* proposed an optimization method based on real-coded genetic algorithm (GA) with elitist strategy for thinning a large linear array of uniformly excited isotropic antennas to yield the maximum relative side lobe level (SLL) equal to or below a fixed level. The percentage of thinning was always kept equal to or above a fixed value. Two examples were proposed and solved with different objectives, and with different values of percentage of thinning that produced nearly the same side lobe level. They showed that the method is very simple and can be used in practice to synthesize a thinned planar array [Mahanti *et al.* (2007)].

Oraizi and Fallahpour investigated non-uniformly spaced linear antenna (NUSLA) arrays rigorously. Several important problems in NUSLA array design were solved with the combination of the genetic algorithm and conjugate gradient method (GA-CG). The pattern synthesis for the specified beam width and minimum achievable side lobe level (SLL) was performed and for the first time, the graphs which show the relation between the beam width, side lobe level and number of elements for NUSLA arrays were derived and plotted [Oraizi and Fallahpour (2008)].

Jainfeng *et al.* applied immune algorithm (IA) to improve the side lobe performance of thinned array. IA was proposed to design arrays by thinned methods using the side lobe level as optimization parameter. The availability of the proposed algorithm was proved by the successful application in pattern synthesis for thinned arrays with both 71% and 77% thinning percentages [Jianfeng *et al.* (2008)].

Ahmed *et al.* devised an empirical relation for the unequally spaced antenna arrays. They carried out the synthesis of uniformly excited, equally and unequally spaced arrays employing physical optics technique to achieve side lobe reduction and narrow beam width by varying the elements number (N) and positions, with equal current magnitude of antenna elements [Ahmed *et al.* (2009)].

Chen *et al.* established a novel aperture release model for synthesis of thinned linear array. They showed that using this model, the elements nearby the center of aperture do not need to be optimized anymore, so solution space of optimization problem can be minimized to some extent accordingly. This new model can reduce computing burden effectively, and improve the efficiency of optimization [Chen *et al.* (2009)].

Deligkaris *et al.* presented the design of thinned planar microstrip arrays under specific constraints concerning the impedance-matching condition of the array elements and the radiation pattern. They applied method-of moments to extract the radiation characteristics of the structures. The array design is based on a novel optimization method, which is a modified version of the Boolean particle swarm optimization that employs velocity mutation (BPSO-vm) [Deligkaris *et al.* (2009)].

Donelli *et al.* presented a hybrid approach for the synthesis of planar thinned antenna arrays. The proposed solution combines the most attractive features of a particle swarm algorithm and those of a combinatorial method based on the noncyclic difference sets of Hadamard type. They demonstrated that as compared to the standard PSO-based optimization, the hybrid strategy allowed a significant improvement in the convergence rate [Donelli *et al.* (2009)].

Lin *et al.* applied the differential evolution (DE) algorithm with a new differential mutation base strategy, namely best of random strategy, to the synthesis of unequally spaced antenna arrays. In the best of random mutation strategy, the best individual among three randomly chosen individuals was used as the mutation base while the other two were used for the vector difference. Hence a good balance of diversity and evolution speed was obtained [Lin *et al.* (2009)].

Oliveri and Massa proposed a genetic algorithm (GA)-enhanced almost difference set (ADS)-based methodology to design thinned linear arrays with low-peak side lobe levels (PSLs). Their method allowed to overcome the limitations of the standard ADS approach in terms of flexibility and performance [Oliveri and Massa (2009)].

Goudos *et al.* proposed unequally spaced linear array synthesis with side lobe suppression under constraints to beam width and null control using a design technique based on a Comprehensive Learning Particle Swarm Optimizer (CLPSO) [Goudos *et al.* (2010)].

Hooker and Arora discussed optimal thinning levels in linear arrays. The scope of this study was to determine the minimum attainable side lobe level for thinned arrays. It was determined that approximately 85%–87% of the total possible elements are required to reach this level for small to medium-sized apertures. As the aperture is increased, the filling percentage decreases [Hooker and Arora (2010)].

Liu *et al.* described a new method for the synthesis of non-uniform linear array with shaped power patterns. The proposed synthesis method consisted of three steps. First, they found a satisfactory power pattern for the required radiation characteristics by solving a constrained least-squares problem which was obtained with the help of non-redundant representation of squared magnitude of a linear array factor. Then, they factorized the polynomial associated with the power pattern by using polynomial rooting, and consequently obtained the corresponding field patterns. Finally, the forward-backward matrix pencil method was used to obtain a non-uniform linear array with optimized excitation magnitudes, phases and locations for a specific choice of field patterns [Liu *et al.* (2010)].

Tan *et al.* used unequal spacing technique not only to reduce the side-lobe level, but also to reduce the number of elements of linear antenna array. They followed arrangements of the elements given by Harrington [Harrington (1961)], and Lo [Lo (1963)], [Tan *et al.* (2010)].

Jain and Mani proposed dynamic thinning of antenna array using genetic algorithm. Dynamic thinning is the process of removing elements under real time conditions. They suggested that stochastic technique is very useful in the design of thinned arrays [Jain and Mani (2011)].

Liu *et al.* presented the synthesis of unequally spaced linear antenna arrays based on an inheritance learning particle swarm optimization (ILPSO). To improve the optimization efficiency of the PSO algorithm, they proposed an inheritance learning strategy that can be applied to various topologies of different PSO algorithms [Liu *et al.* (2011)].

Oliveri and Massa introduced a numerically efficient technique based on the Bayesian compressive sampling (BCS) for the design of maximally sparse linear arrays. The method was based on a probabilistic formulation of the array synthesis and exploited a fast relevance vector machine (RVM) for the problem solution. The proposed approach allowed the design of linear arrangements fitting the desired power patterns with a reduced number of non-uniformly spaced active elements [Oliveri and Massa (2011)].

Dev *et al.* employed a hybridized optimization technique called ‘particle swam optimization with differently perturbed velocity’ for two different types of thinned array design problems and the performance was compared with those of particle swam optimization and differential evolution [Deb *et al.* (2012)].

Wang *et al*. presented a modified iterative Fourier technique (MIFT) for thinning uniformly spaced linear arrays featuring a minimum side lobe level as well as narrow beam. They proposed an adaptively changed fill factor in MIFT, based on the idea of gradual thinning, which was inspired by perturbation theory, to modify IFT with the purpose of accelerating computational speed and facilitating convergence [Wang *et al.* (2012)].

Zaman and Matin synthesized a non-uniformly spaced linear antenna array with broadside radiation characteristics using firefly algorithm and particle swarm optimization. The objective of the work was to find the optimum spacing between the radiating antenna elements, which created a predefined arbitrary radiation pattern. The excitation amplitudes of all the antenna elements were assumed to be constant. The optimum spacings between the array elements were obtained using firefly algorithm. The minimum allowed distance between the antenna elements was defined in such a way that mutual coupling between the elements was ignored [Zaman and Matin (2012)].

Zhang *et al.* utilized an orthogonal genetic algorithm (OGA) to optimize the planar thinned array with a minimum PSLL. The method is a genetic algorithm based on orthogonal design. A crossover operator formed by the orthogonal array and the factor analysis was employed to enhance the genetic algorithm for optimization [Zhang *et al.* (2012)]. .

Bhargav and Gupta proposed a new technique for realizing a non-uniform linear array with low side lobe level (SLL) and beam width. The technique utilizes multiple-objective functions for this purpose. These functions were applied in a cyclic fashion to optimize the spacing, excitation, and phase variation of the elements using the genetic algorithm [Bhargav and Gupta (2013)].

Yang *et al.* reduced the computational cost of large array pattern synthesis, which was attractive in many applications. A fast pencil beam pattern synthesis method for large non-uniform antenna arrays was proposed. This method was based on an interpolation in a least square sense and iterative fast Fourier transform (FFT) [Yang *et al*. (2013)].

Ha *et al.* presented the synthesis of thinned arrays by means of optimization using compact genetic algorithm (cGA). The optimization algorithm implements a probability vector to represent the population, which was suitable to apply to thinned array problem [Ha *et al.* (2014)].

Lin and Wu proposed an improved binary invasive weed optimization (IBIWO) to design thinned arrays with minimum side lobe levels .They introduced the use of IBIWO algorithm for thinning periodic linear and planar arrays to obtain the lowest possible peak side lobe levels [Liu and Wu (2014)].

Nihad studied the design of thinned planar antenna arrays of isotropic radiators with optimum side lobe level reduction. The teaching–learning based optimization (TLBO) method, a newly proposed global evolutionary optimization method, was used to determine an optimum set of turned-ON elements of thinned planar antenna arrays that provided a radiation patterns with optimum side lobe level reduction [Nihad (2014)].

You *et al.* presented a hybrid approach to synthesize unequally spaced antenna arrays with low side lobes. The exact locations of all the elements for unequally spaced antenna arrays were quickly determined with the help of composite Taylor–exponent configuration arrangement [You *et al.* (2015)].

1.3 Research Objectives

In this dissertation, author investigates synthesis methods based on global optimization techniques for the design of sparse (thinned, non-uniformly spaced and multi-functional) antenna arrays, capable of satisfying many radiation pattern requirements, such as minimum possible SLL, narrow HPBW and higher gain or directivity for given size of aperture, main beam scan capability etc. essential for radar applications. The main objective of the proposed synthesis methods is to overcome the limitations of current synthesis techniques, which are either computationally inefficient or do not exhibit a good design performance. Genetic algorithm (GA) and particle swarm optimization (PSO) techniques are employed to find optimum solutions for problems at hand. Some novel advancement in GA and PSO control parameters are devised to enhance their synthesis capabilities in terms of computational load and design performance. Author carried out following studies as part of his Ph.D. research work:

- Figured out the significances of thinning and variable inter-element spacing in different configurations (linear or planar) of antenna arrays and formulate them as optimization problems
- Studied GA and PSO optimization algorithms and employ them in the development of various synthesis approaches for solving thinning and variable inter-element spacing problems in antenna arrays
- Developed sparse antenna array optimization tool in MATLAB by utilizing aforesaid algorithms and investigated solutions for various problems under consideration.
- Verified the solutions for some of the problems through appropriate simulation and experimental studies.
- Identified the problems for future research work so that further studies can be carried out by other interested researchers

1.4 Motivation and Problem Definition

As mentioned before, advantages of utilizing sparse antenna arrays are not limited to cost and mutual coupling. Several other characteristics including bandwidth, weight, power consumption, heat dissipation and multi-functionality are also anticipated to ameliorate. Keeping in view the afore-said characteristics and requirements of active antenna arrays for radar applications, author felt meaningful to find some novel ideas and approaches to reduce these constraints. The following aspects have further augmented the author to carry out research in this area:

- Very limited work has been reported on thinned and non-uniformly spaced antenna arrays for practical applications. Maximum research has been limited to the numerical analysis only.
- Proposed study is an inter-disciplinary work, which involves electromagnetic and computational techniques; therefore, possibility exists to learn and understand new disciplines.
- The outcome of the proposed research work is expected to have practical relevance in military radar applications.

1.5 Contribution and Scope of the Research Work

State-of-the-art in this frame work demonstrates that the approaches for finding suitable solutions for thinned and non-uniformly spaced sparse array configurations have been tried mostly based on Genetic Algorithm (GA) and Particle swarm optimization (PSO). Although these techniques have been successfully employed by many researchers for solving various antenna array problems, the solution obtained through them might not be optimum. Development of suitable search techniques can address problems involving various constraints for the design of sparse antenna arrays for radar application and provide efficient solutions in terms of flexibility and design performance.

Keeping foregoing aspects in view, following work plan/approach is adopted for the present investigation:

- The sparse antenna array problems are formulated in three possible ways
    - Removing (turning off) some antenna elements from a periodic or uniformly spaced array to create a desired current distribution on the array aperture corresponding to the required radiation pattern characteristics

  - Non-uniformly varying the geometric positions of antenna elements of the periodic arrays
  - Randomly varying the geometric positions of antenna elements of periodic arrays

- The search strategies are implemented using GA and PSO based optimization techniques. The reason for selecting these techniques was based on their simplicity, ease of implementation, and adaptability. Results obtained using the proposed techniques are expected to be superior/comparable with similar published results. The following bench mark problems are chosen for assessing the array performance through comparison of results with those published in the literature:
  - PSLL optimization in 100-element TLA array at antenna boresight
  - Maximization of reduction in PSLL and number of 'OFF' elements in 100- and 200-element TLA arrays
  - PSLL optimization in 100-element TLA array at boresight as well as $\pm 60^0$ scan angles
  - Optimization of PSLL, HPBW, and gain in 100- element TLA array
  - PSLL optimization in 24-element NUSLA array at boresight
  - PSLL optimization in 16-and 32-element NUSLA arrays by devising optimum elements' density on the array aperture
  - PSLL optimization at boresight as well as $\pm 30^0$ scan angles in 16-element NUSLA array
  - Optimization of PSLL in uniformly excited and amplitude weighted 36-element NUSLA array

  - To further validate the performance of proposed synthesis methods, appropriate EM simulation and experimental studies on 24-element NUSLA array are carried out

- After establishing the optimization strategies for TLA and NUSLA arrays, the same are extended for the synthesis of TPA and NUSPA arrays. Results obtained by proposed strategies are compared with the results reported in the literature. The following bench mark problems are considered for assessing the performance of these synthesis approaches:
  - PSLL optimization at antenna boresight in 10×20-element TPA array
  - PSLL optimization in 10×10- and 14×14-elements TPA arrays over $\pm 40^0$ scan volume
  - Peak, average, and RMS SLLs optimization in 10×20-element TPA array
  - PSLL optimization by jointly determining thinned configuration and amplitude weights in 10×20- and 8×8-elements TPA arrays
  - PSLL optimization in 8×16-element UE-NUSPA array
  - PSLL optimization in 8×16-element AW- NUSPA array
  - In order to further affirm the capability of proposed synthesis method, appropriate EM simulation and experimental studies on 8×8-element AW-TPA array are performed.
- The optimization approach developed for the design of NUSPA arrays is further extended to optimize RSPA and MFA arrays. The bench mark problems as listed below are assumed for evaluating the performance of this synthesis approach.
  - PSLL optimization in 8×16-element RSPA array
  - Design of 4×4- and 8×8-element multi-functional antenna arrays sharing the same physical aperture

1.6 Outline of the Thesis

This dissertation is organized in five chapters. Chapter 1 covers the theoretical background of sparse antenna arrays and the previous research studies conducted in this frame work, along with the necessity and motivation for the present investigation for radar application. The summary of the contributions made by the author, and an outline of the structure of thesis are also presented in this chapter.

In chapter 2, development of various synthesis strategies to design sparse linear antenna (TLA and NUSLA) arrays based on GA and PSO optimization methods is reported. Research work in this chapter is divided into four parts on TLA arrays and five parts on NUSLA arrays with various problems of interest. The chapter starts with the problem formulation and synthesis of uniformly excited linear thinned array, which provides maximum possible reduction in PSLL. The capability of proposed synthesis method is shown through the analysis of 100-element TLA array. In the second part of study on TLA arrays, an innovative thinned array synthesis approach based on MBC-GA is presented, which yields maximum possible reduction in PSLL with great stability in a computationally efficient manner. Performance is assessed by carrying out a numerical analysis of uniformly excited 100- and 200-element TLA arrays. In the third part of study on TLA arrays, synthesis approach based on PSO optimization technique is demonstrated, which provides maximum possible reduction in PSLL at antenna boresight as well as upto ± 60^0 scan angles with respect to antenna boresight. The usefulness of PSO search algorithm to synthesize TLA array at boresight as well as upto 60^0 scan angles with respect to antenna boresight is described through the analysis of uniformly excited 100-element linear array. In the fourth part of study on TLA arrays, synthesis method utilizing GA which yields reduced PSLL, narrow HPBW and higher gain/directivity is successfully demonstrated through the analysis of uniformly excited

100-element linear antenna array. In the first part of research work on NUSLA arrays, GA based synthesis technique, which deals with reduction in PSLL in uniformly excited NUSLA array is demonstrated. In the second part of research work on NUSLA arrays, a simple, effective and computationally efficient approach for the synthesis of uniformly excited NUSLA arrays is presented. The proposed approach deals with determination of optimum elements' density at the aperture, which empowers the synthesis technique with flexibility and increased search competency in attaining maximum possible reduction in PSLL. The IW-PSO algorithm is employed for the proposed synthesis. Two NUSLA arrays consisting of 16-and 32-elements are numerically analysed to assess the effectiveness of proposed approach. In the third part of research work on NUSLA arrays, an optimization approach to synthesize a steerable array pattern in NUSLA is demonstrated. The particle swarm optimisation (PSO) synthesis technique is applied to adjust the locations of array elements for obtaining the lowest possible PSLL at boresight as well as over pre-specified scan angles away from boresight. To demonstrate the performance of proposed method, a 16-element uniformly excited NUSLA array is examined in this study. In the fourth part of research work on NUSLA arrays, a novel strategy based on PSO for the synthesis of NUSLA array which deals with jointly optimizing the spacings and amplitude excitations of the optimum number of edge elements is presented. The performance of proposed approach is evaluated by numerically analysing a 36-element NUSLA array. In the last part of research work on NUSLA arrays, the performance of 24-element NUSLA array which was numerically analysed in the first part of research work on NUSLA arrays is further validated through EM simulation and experimental study.

Chapter 3 describes the synthesis approaches to design sparse planar antenna (TPA and NUSPA) arrays. The synthesis approaches developed for linear arrays are extended to synthesize sparse planar antenna arrays in this chapter. Research work in this chapter is divided into five parts on TPA arrays and one study on NUSPA arrays with various objectives under consideration.

In the first part of research work on TPA arrays, an innovative synthesis approach using MBC-GA is presented, which yields maximum possible reduction in PSLL with great stability in a computationally efficient manner. To demonstrate the capability of proposed method, a 10×20-element TPA array is numerically examined. In the second part of research work on TPA arrays, an IBc-GA optimization technique based thinned array synthesis approach is demonstrated. To clearly point out the innovative contents and motivation of new variant of GA, numerical analysis of 10×10- and 14×14-element UE-TPA arrays are presented. In the third part of research work on TPA arrays, synthesis of thinned planar array using PSO with the objective to minimize peak, RMS and average SLLs is demonstrated through the analysis of uniformly excited 10×20-element TPA array. In the fourth part of research work on TPA arrays, an efficient synthesis technique, which deals with optimization of both thinned array configuration and thinned configuration along with amplitude coefficients of array elements to achieve low PSLL is devised and its performance in terms of design efficiency is evaluated by analysing 10×20- and 8×8 elements TPA arrays. In the fifth part of research work on TPA arrays, the EM simulation and experimental evaluation of 8×8-element AW-TPA array, which was numerically analysed in the fourth part of TPA array study, are performed. This is done to further validate the potentialities, implications and functioning of synthesized TPA array in practical scenario. In the first part of research work on NUSPA array, a novel strategy for synthesis of 8×16-element UE-NUSPA array is described. In the second part of this research work, a novel strategy, which deals with jointly optimizing the inter-element spacings and amplitude excitation coefficients for the optimum number of edge elements, is presented by assuming 8×16-element AW-NUSPA array.

In chapter 4, the synthesis approaches to design randomly spaced and multi-functional planar antenna (RSPA and MFA) arrays are described. The synthesis approach developed for sparse planar antenna (NUSPA) arrays is extended to design randomly spaced planar antenna and multi-functional antenna arrays. This synthesis approach takes into consideration the mutual coupling effect and physical size of the antenna elements. A new formulation based on MBC-GA is proposed for the synthesis of RSPA arrays in which elements are randomly distributed on the aperture to obtain lowest possible PSLL. To corroborate the performance of proposed synthesis strategy, a 8×16-element RSPA array operating at 3.3 GHz, 4×4-elements RSPA array operating at 1.5 GHz and 8×8-elements RSPA array operating at 3.3 GHz are numerically analysed. Multi-functionality from single aperture are obtained using shared aperture array concept by combining two RSPA arrays, one operating at 1.5 GHz and the other at 3.3 GHz.

Significant outcomes of the present investigation on the design of sparse antenna arrays are presented in Chapter 5. Major conclusions are drawn based on the present study. Open problems are also identified. In addition, this chapter also outlines the scope for further research in this framework.

The references are included as the significant source of material for different types of thinned/non-uniform/randomly spaced antenna arrays related to present work.

At the end, appendices are included which describe the implementation of optimization techniques in MATLAB and Graphical User Interface which pictorially represents the developed optimization tool.