CHAPTER 5

SUMMARY, CONCLUSION AND FUTURE SCOPE

5.1. Summary and Conclusion

In this dissertation, new synthesis techniques have been developed for optimizing sparse antenna arrays of varying sizes and shape with the objective to meet radar antenna array requirement including low SLLs, and narrow and highly directive main beam. These synthesis methods based on GA and PSO optimization techniques have been developed to overcome the limitations of existing state-of-the-art synthesis techniques in terms of either computational efficiency or design performance. It has been shown from the results obtained through the proposed methods for various arrays under consideration that some novel advancements in control operators of basic GA and PSO have improved the solution quality of these methods. As part of this research work, a new GUI using MATLAB ver. 8 has been developed, which helps user to optimize sparse array configurations, even if they are not familiar with the architecture of optimization methods and their implementation in MATLAB. A brief summary of the chapters borne out of this research is presented below.

In **Chapter 1,** the problems faced in modern military radar systems and reviews of the existing literature related to the research carried out by the author have been discussed.

In **Chapter 2**, development of various synthesis approaches to design sparse linear antenna (TLA and NUSLA) arrays based on GA and PSO optimization techniques has been considered. Research work in this chapter is divided into four parts on TLA arrays and five parts on NUSLA arrays with various problems of interest. Outcomes of each part are described below.

In the first part of research work on TLA arrays, synthesis approach based on GA has been developed which provides maximum possible reduction in PSLL for uniformly excited TLA array. The capability of presented synthesis method has been demonstrated through the analysis of 100-element TLA array. The results obtained through the proposed method show that PSLL < -21.95 dB has been achieved for the array under consideration.

In the second part of research work on TLA array, an innovative thinned array synthesis approach based on MBC-GA has been successfully presented which yields maximum possible reduction in PSLL. This solution has been achieved with great stability in a computationally efficient manner. It has been shown from the numerical analysis of uniformly excited 100- and 200-element TLA arrays that significant amount of improvement in PSLL with large thinning percentage has been obtained using the proposed synthesis technique. This has confirmed that the proposed MBC-GA optimization technique has significantly outperformed the state-of-the-art synthesis techniques reported in [Mahenti et al. (2007)], [Teruel and Iglesias (2006)], and [Wang et al. (2012)] in terms of design performance. It has also been demonstrated that the computational load involved in the proposed method is much less than those associated with the methods reported in [Mahenti et al. (2007)], and [Wang et al. (2012)]. This has ensured that the MBC-GA technique is computationally more efficient as compared to existing state-of-the-art synthesis methods. In addition, the stability of MBC-GA technique has been demonstrated by executing 30 independent trials, and results obtained for the arrays under consideration have been averaged over all the trials. It has been observed from the reported results that the best PSLL has been obtained in single trial and PSLL averaged over all the trials are almost equal which confirmed the reliability of proposed approach. Therefore, it can be concluded that the investigated innovative robust randomization strategy for crossover operation and unexampled systematic mutation strategy successfully presented in present study have enhanced the solution quality in terms of design performance. This has helped in achieving lowest possible PSLL using less number of turn 'ON' elements with great stability in a computationally efficient fashion. It is expected that the investigated MBC-GA synthesis technique would be useful for interested researchers to design thinned arrays of any size and shape.

In the third part of research work on TLA arrays, synthesis approach based on PSO optimization technique has been demonstrated, which provides maximum possible reduction in PSLL at antenna boresight as well as upto $\pm 60^0$ scan angles with respect to antenna boresight. The usefulness of PSO search algorithm to synthesize TLA array at boresight as well as upto $\pm 60^0$ scan angles with respect to antenna boresight has been described through the analysis of uniformly excited 100-element linear array. The performance of proposed method in terms of suppression of side lobe level has been evaluated and compared with the results obtained for the fully filled linear array having all the elements turned 'ON' and with the results published in literature. It has been found that the PSLL obtained using the proposed synthesis of TLA array is less than -22.58 dB, which is lower by 1.29 - 2.06 dB as compared to the synthesis techniques reported in the literature [Teruel and Iglesias (2006)], [Mahanti et al. (2007)], and [Wang et al. (2012)]. Further, synthesis of the proposed 100-element TLA phased array scanned upto $\pm 60^0$ angle has been reported and its performance has been compared with that at antenna boresight. It has been found that the array is steerable up to $\pm 60^0$ without significant degradation in PSLL. Hence, it can be concluded that the proposed technique seems to be very effective in thinning of both TLA array at boresight as well as the array steered upto pre-specified scan angles.

In the fourth part of research work on TLA arrays, synthesis method based on GA has been successfully demonstrated through the analysis of uniformly excited 100-element linear array. The performance of proposed method in terms of PSLL, HPBW and gain has been evaluated and compared with the previously published results. It has been shown that the PSLL obtained using the proposed synthesis approach is better than -21.57 dB, which is lower by 1.01 and 1.05 dB respectively as compared to the synthesis techniques reported in the literature [Haupt (1995)], and [Teruel and Iglesias (2006)]. The HPBW is lower by .07 and 0.15, and directivity is higher by 0.26 and 0.38 respectively as compared with those using the preceding techniques. Thus, it can be concluded that the proposed technique is more effective in thinning of TLA arrays with reduced PSLL while at the same time providing narrow main beam and higher directivity.

In the first part of research work on NUSLA arrays, GA based synthesis technique, which deals with reduction in PSLL in uniformly excited 24-element NUSLA array has been demonstrated. The capability of proposed method in terms of reduction in PSLL has been compared with those reported in literature. It has been found from the reported results that the proposed method offers more PSLL suppression in the range of 0.37 to 2 dB as compared to the synthesis techniques reported in [Goudas et al. (2010)] and [Caratelli and Vigano (2011)]. This has confirmed that the proposed method is more capable in minimizing PSLL in NUSLA arrays compared to the existing state-of-the-art methods.

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 has been demonstrated. The proposed approach dealt 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 has been employed in the proposed synthesis approach. Initially, the optimal number of unequally spaced elements of the NUSLA arrays has been investigated and a mathematical relation was formulated to approximate the optimum percentage of unequally spaced elements as a function of total number of elements. This has been applied to NUSLA arrays composed of 8 to 64 elements in order to provide flexibility and enhance the global search ability of the available optimization algorithms. Two NUSLA arrays consisting of 16-and 32-elements have been numerically analysed to assess the effectiveness of proposed approach. The numerical results obtained through the proposed technique have been compared with those using other techniques available in the literature [Chen et al. (2006)], [Goudos et al. (2010)], [Goudos et al. (2011)], [Lin et al. (2010)], [Lin et al. (2012)], and [Zhang et al. (2013)]. This has evidenced that the proposed approach outperforms other schemes including afore-mentioned ones. Therefore, it can be concluded that proposed scheme offers great flexibility as well as enhances the global search ability of IW-PSO algorithm in achieving lowest possible PSLL at reduced computational cost.

In the third part of research work on NUSLA arrays, an optimization approach to synthesize a steerable array pattern in NUSLA has been demonstrated. The particle swarm optimisation (PSO) synthesis technique has been applied to adjust the locations of array elements for obtaining lowest possible PSLL at boresight as well as over pre-specified scan angles. In order to demonstrate the performance of proposed method, a 16-element uniformly excited NUSLA array has been examined in this study. Results obtained through the proposed scheme has shown that this method for pattern synthesis of 16-element NUSLA array is able to significantly reduce the PSLL without appearance of grating lobes over the scan volume under consideration. Therefore, results obtained using the proposed synthesis technique authenticates the validity of proposed method. It can be concluded that this approach is very much useful to design NUSLA arrays for electronically scanned array based radar applications.

In the fourth part of research work on NUSLA arrays, a novel strategy based on PSO for the synthesis of NUSLA array that deals with jointly optimizing the spacings and amplitude excitations of the optimum number of edge elements has been successfully presented. The perfomance of proposed approach has been evaluated by numerically analyzing 36-element NUSLA array and comparing its results with the published results for NUSLA arrays of similar size reported in [Chen et al. (2006)], [Cen et al. (2012)], [Lin et al. (2010)], and [Zhang et al. (2011)] and with those for Taylor-tapered uniformly excited arrays. It has been found that the proposed technique has provided lower PSLL at reduced computational cost while maintaining narrow HPBW and high directivity. This shows that the proposed approach of optimizing spacings and amplitude excitations of the optimum number of edge elements in united way has great potential in obtaining lower PSLL while maintaining narrow and highly directive main beam.

In the fifth part of research work on NUSLA arrays, the performance of 24-element NUSLA array, which was numerically analysed in the first part of the research work on NUSLA arrays, has been further validated through EM simulation and experimental study. An extensive EM simulation study of the proposed array was carried out using HFSS Ver. 13 EM software by assuming M-shaped patch [Aggarwal and Gangwar (2014)] as a basic radiating element. Numerical and EM simulation results have been compared. It has been found through comparison of results that the simulated radiation pattern of the NUSLA array has not been severely impacted, except for the first side-lobe level, which has been degraded from -26.9 dB to -20.7 dB, and the gain, which has reduced by 0.68 dB. This means that the proposed synthesis method yields moderately optimistic results in practical operating scenario where the effect of mutual coupling cannot be ignored.

Chapter 3 describes the synthesis approaches to design sparse planar antenna (TPA and NUSPA) arrays. The synthesis approaches developed for linear arrays in chapter 2 were extended to synthesize sparse planar antenna arrays in this chapter. Research work in this chapter has been divided into five studies on TPA arrays and two studies 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 has been successfully presented for TPA array, which yields maximum possible reduction in PSLL with great stability in a computationally efficient manner. In order to demonstrate the capability of proposed method, a 10×20-element TPA array has been numerically examined. It has been shown from the numerical analysis of arrays under consideration that significant amount of improvement in PSLL with large thinning percentage has been obtained using the proposed synthesis technique. This has confirmed that the presented MBC-GA has significantly outperformed the state-of-the–art synthesis technique reported in [Teruel and Iglesias (2006)], [Zhang et al. (2010)], [Wang et al. (2012)], and [Liu and Wu (2014)] in terms of design performance. It has also been demonstrated that the computational load involved in the proposed method is much less than that associated with methods reported in [Liu and Wu (2014)], and [Wang et al. (2012)], which has ensured that the MBC-GA technique is computationally more efficient. In addition, the stability of MBC-GA technique has been shown by executing 30 independent trials and results obtained for the arrays under consideration have been averaged over all the trials. It was observed from the reported results that the best PSLL obtained in single trial and PSLL averaged over all the trials are almost equal which confirmed the reliability of proposed approach.

In the second part of research work on TPA arrays, an IBc-GA optimization technique based thinned array synthesis approach has been shown. In order to clearly point out the innovative contents and motivation of new variant of GA, numerical analyses of 10×10- and 14×14-element UE-TPA arrays have been presented. The performance obtained through the proposed approach in terms of reduction in PSLL and computational burden has been numerically evaluated and compared with those reported in the literature. It has been demonstrated that the PSLL achieved through the proposed synthesis technique for 10×10-element UE-TPA array is much better with less number of turn 'ON' elements than those obtained through the techniques reported in [Zhang et al. (2010)], [Deb et al. (2012)], and [Nihad (2014)] at comparable computational load. The synthesized array was further steered at 20^0 and 40^0 scan angles and its radiation characteristics have been compared with those of the arrays at boresight. In addition, results at antenna boresight achieved by the proposed method for the case of 14×14-element UE-TPA array have been compared with those obtained at 20^0 and 40^0 scan angles. It has been observed that there was no significant degradation in PSLL and appearance of grating lobes when the arrays under consideration were steered at aforesaid angles away from boresight. Therefore, the presented results have confirmed that the devised novel concept of multi-segment chromosomes as well as new methods for crossover and mutation operations in IBc-GA have ameliorated the adaptability in the search for an optimum solution as well as potentiated the global search competency of standard GA in achieving lowest possible peak side lobe level (PSLL) at affordable computational cost. Hence, it can be concluded that demonstrated distinct results and features have strongly asserted that the presented IBc-GA is an efficient synthesis tool as compared to standard GA and other state-of-the-art synthesis techniques available in literature. It is hoped that IBc-GA based synthesis approach would definitely be informative for interested researchers to design TPA arrays with wide beam steering capability and definitely help in achieving the maximum possible reduction in PSLL at affordable computational burden.

In the third part of research work on TPA arrays, synthesis of thinned planar array using PSO with the objective of minimizing peak, RMS and average SLLs has been successfully demonstrated through the analysis of uniformly excited 10×20-element TPA array. The performance of proposed method in terms of suppression of peak, RMS and average side lobe levels has been evaluated and compared with the methods reported in the literature. It has been found that the peak, RMS and average side lobe levels obtained using the proposed synthesis technique are better as compared to those obtained in [Haupt (1994)], [Teruel and Iglesias (2006)] and [Zhang et al.(2010)]. It has also been observed from 3D radiation pattern of the proposed array that no SLL is greater than -19 dB in any plane of the proposed thinned antenna array visible region resulting into better average SLL. The HPBW and directivity of the proposed array are almost same as those of a fully dense array of equal size. Hence, it can be concluded that the proposed technique seems to be more effective in thinning of planar arrays with reduced PSLL without affecting the HPBW and directivity.

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 has been devised and its performance in terms of design efficiency has been evaluated by analysing 10×20- and 8×8 elements TPA arrays. A modified binary coded genetic algorithm (MBC-GA) employing novel meliorated techniques for crossover and mutation operations has been established for the synthesis of TPA arrays with maximally reduced PSLL. Initially 10×20- and 8×8-elements UE-TPA arrays were analysed and the effectiveness of the proposed synthesis technique and its performance comparison for 10×20-element UE-TPA array with those reported in the literature [Teruel and Iglesias (2006)], [Zhang et al. (2010)], [Wang et al. (2012)] , and [Liu and Wu (2014)] have been demonstrated. It has been found from the numerical results obtained through the synthesis of the arrays under consideration that the proposed MBC-GA has provided significant improvement in PSLL performance. Furthermore, the synthesis of 10×20- and 8×8-elements AW-TPA arrays has been successfully demonstrated in which both amplitude weight and thinned arrangements were jointly optimized and about 2-3 dB further reduction in PSLL was achieved without altering HPBW.

In the fifth part of research work on TPA arrays, the EM simulation and experimental evaluation of 8×8-element TPA array, which was numerically analysed in the fourth part of study on TPA array, have been carried out to further validate the findings, implications and functioning of synthesized TPA array in practical scenario. The experimental results have been found nearly in agreement with the simulated and numerically computed ones. Therefore, it can be concluded that the investigated MBC-GA based synthesis technique is very efficient for the design of TPA arrays for practical applications.

In the first part of research work on NUSPA array, a novel strategy for the synthesis of 8×16-element UE-NUSPA array that deals with optimizing the inter-element spacings alone has been presented. In the second part of research work on NUSPA array, synthesis of 8×16-element AW-NUSPA array that deals with jointly optimizing inter-element spacings and amplitude excitation coefficients of the optimum number of edge elements has been successfully presented. The numerical results obtained through the proposed approach for the synthesis of AW- NUSPA arrays have been compared with that of Taylor-tapered uniformly spaced array. It has been found that the HPBW and directivity of the proposed NUSPA arrays are slightly better as compared with equivalent Taylor tapered uniformly spaced array of similar size. Additionally, the SLLs obtained in all the planes (inter-coordinal and principal) using the proposed synthesis approach are better than -18 dB. It has also been demonstrated that the number of parameters involved in the optimization of proposed method are 45% less than those reported in [Chen et al. (2006)], [Lin et al. (2010)], [Zhang et al. (2011)], and [Cen et al. (2012)] and hence relatively less computational cost is involved in the present study. Therefore, it can be concluded that the proposed technique has provided lower SLL at reduced computational cost for the synthesis of both UE- and AW-NUSPA arrays while maintaining narrow HPBW and high directivity. This means that proposed approach of optimizing spacings and amplitude excitations of the optimum number of edge elements in united way has shown great potential in obtaining low PSLL while maintaining narrow and highly directive main beam.

In **chapter 4**, synthesis approaches to design randomly spaced and multi-functional planar antenna (RSPA and MFA) arrays have been described. The PSO based synthesis approach developed for sparse planar antenna (NUSPA) arrays in chapter 3 was modified to establish new approach based on MBC-GA for the syntheses of randomly spaced and multi-functional planar antenna arrays in this chapter. These approaches have taken into consideration the mutual coupling effect and the physical size of antenna elements.

An MBC-GA based synthesis strategy for the design of MFA array consisting of differently sized radiating elements arranged in sparse configuration has been successfully demonstrated. Initially, synthesis of RSPA array with reduced PSLL in both the planes has been successfully implemented. The performance of proposed method has been verified by numerically analysing 8×16-element RSPA array. The results have proved that a significant amount of reduction in PSLL has occurred with uniform amplitude excitation. This authenticates the validity of the proposed method for the synthesis of RSPA arrays.

Later on, multi-functionality based on shared aperture concept has been demonstrated through the analyses of two sub-arrays operating at 1.5 GHz and 3.3 GHz in the same aperture of physical antenna system. The results have shown that proper formation of main beam has occurred with uniform amplitude excitation. Therefore, it can be concluded that, a new solution to design multi-functional antenna array based on the concept of interleaving two RSPA sub-arrays operating at different frequencies has been successfully proven by this study.

5.2. Future Scope

The synthesis approaches to design sparse antenna (thinned, non-uniformly spaced, randomly spaced, and multi-functional) arrays have been successfully presented in this thesis.

During the research stage, new challenges related to capabilities and the limitations of sparse antenna arrays for radar applications, which require further investigations, have been identified and listed as follows:

- The evident next step would be to carry out further research work on design of sparse planar antenna array, which deals with a larger number of antenna elements (of the order thousands or multiple of thousands). This problem could be solved by adopting the optimization approaches discussed in chapter 3

- Another interesting practical application would be realizing sparse antenna array with shaped beam especially $cosec^2$ radiation pattern through the determination of optimum antenna (thinned or non-uniformly spaced) array configurations
- Another topic of interest would be the study on conformal sparse antenna arrays
- Outcomes arising out of the solutions on the problem of interest in this dissertation have shown that suppression of PSLL has been achieved in principal planes. However, it was very difficult to obtain suppression in inter-coordinal planes, which rendered poor average and RMS side lobe levels. This is probably due to non-linear dependency of radiated far field on the elements' density, which is the fundamental limitation of the sparse (thinned or non-uniformly spaced) antenna arrays
- A new solution, to design multi-functional antenna array based on the concept of interleaving two different frequencies RSPA sub-arrays in single aperture, has been established. However, further investigations are required to obtain desired radiation pattern characteristics.

Finally, to overcome the limitations of present investigation, further research would be very valuable in the context of sparse antenna arrays for radar applications.