CHAPTER 5

CONCLUSIONS

The number of both unwanted directional interferences and strong nearby sources, which degrade the performance of a communication system, increase as communication networks expand. The signal-to-interference ratio (SIR) can be improved by using multiple nulls in the directions of the interferences while maintaining omnidirectional coverage in the direction of the users. In this thesis, cylindrical microstrip patch antenna arrays were investigated as an antenna to provide an omnidirectional radiation pattern with nulls at specified angular locations to suppress interference from directional sources.

5.1 Null synthesis using cylindrical microstrip patch arrays

Three null synthesis methods were described and used to provide the omnidirectional array pattern with nulls using the radiation characteristics of the cylindrical microstrip patch antenna elements. In addition, the implementation of the cylindrical microstrip patch array was investigated. The effect of coupling on the resulting null pattern was investigated and a mutual coupling compensation technique was applied to correct the array radiation pattern by adjusting the active driving impedances of the array elements.

Previously, Abele et al. [53] introduced a null synthesis technique for a cylindrical dipole array. The technique utilised the orthogonal projection method and projected an idealised null pattern onto the orthogonal base of realisable array patterns. The resulting array pattern was an omnidirectional pattern with one or more nulls. Vescovo [56] extended the orthogonal projection method for an arc array with theoretical directional elements. A beam pattern was formed through the projection method and additional nulls were introduced in the pattern with null constraints to reduce the side lobe level. In this study, the null synthesis technique of Abele was extended to incorporate the directional radiation patterns of the cylindrical microstrip patches. The null synthesis technique was then used to form an omnidirectional radiation pattern with nulls at desired locations.

The orthogonal projection method was extended by modifying the orthogonal base for the space of realisable array patterns to include the radiation pattern characteristics of microstrip patches mounted on a conducting cylinder. The orthogonal base was modified for both axially and circumferentially polarised microstrip patch arrays. The unconstrained optimum element excitations obtained from the orthogonal projection method provided an optimal array pattern with the least pattern error. By applying a Hamming window to the sequence excitations before the element excitations were computed, the gain ripple in the omni-region was reduced. The influence of the array configuration on the resulting null pattern characteristics was investigated extensively for both patch array polarisations and a cylindrical array of dipoles. The resulting null pattern characteristics were compared for various numbers of elements and inter-element spacing. In most cases, the microstrip patch arrays yielded better gain ripple in the omni-region of the radiation pattern than dipole arrays.

Since the amplitude and phase of the radiation pattern were optimised simultaneously, the optimal array pattern may not have had the desired characteristics. When a small number of elements was used, the resulting gain ripple in the omni-region was high (more than 2-3 dB). Although the ripple was successfully decreased by using the windowing function of Abele [53], the resulting null width was increased. When maximum omni-coverage and narrow nulls are required, the increase in the null width is a disadvantage. Instead of only minimising the array pattern error, a multi-objective optimisation approach was followed [95–97]. The objective weighting method, previously applied in other fields of computational electromagnetic problems [96, 97], was used to improve the amplitude pattern characteristics.

A global performance function was defined by utilising both the amplitude pattern error and the phase pattern error. The optimisation problem was solved by finding the critical ratio of the weights that were assigned to the two errors in the performance function. Each performance function was minimised by using an unconstrained minimisation algorithm [99]. The excitation vector obtained from the orthogonal projection method yielded an optimum radiation pattern with the minimum pattern error and was therefore chosen as the starting vector.

The excitation vector that minimised the performance function formed with the critical weight ratio, was used to form the radiation pattern. The objective weighting method provided a null pattern with a narrower and deeper null and with a higher gain ripple in the omni-region. An increase in the phase pattern error was observed due to the tradeoff that existed between the two pattern errors in the performance function. Using this method, deep nulls could be obtained utilising only a small number of elements.

Another way of improving the resulting radiation pattern is to provide control over the individual characteristics. In some applications, the degree of suppression needs to be specified through a controllable null depth. Abele [54] proposed a variable phase step to provide control over the null depth. The accuracy of the resulting null depth depended on the array configuration and the desired null depth. Constrained optimisation provides a method of constraining the different attributes of the amplitude pattern while minimising the array pattern error. A constrained optimisation method was utilised to provide control over the different null pattern characteristics.

Previously, Prasad [45] applied the least squares optimisation method to circular and arc arrays to form a beam pattern with a specified beamwidth. Additional nulls were also placed in the sidelobe region by using null constraints while minimising the mean square difference between the desired pattern and the optimum pattern. The Hook and Jeeves algorithm was also used to perform an iterative search to find the optimum excitation vector while satisfying the null constraints. Ares *et al.* [52] used a simulated annealing technique to produce beam patterns for a circular arc array on a cylinder. A cost function, which could include terms to control the radiation pattern, was minimised. Terms which placed constraints on the excitations, could also be included in the cost function.

A constrained minimisation algorithm [99] was used in this study to yield an excitation vector which minimises the pattern error under the constraints specified for the different null pattern characteristics (e.g. gain ripple in the omni-region, the null width and null depth). Individual characteristics as well as combinations of characteristics were controllable using the constrained optimisation. Due to the control provided by this method, the pattern characteristics became independent of the number of elements and the inter-element spacing. Multiple nulls with different null depths were also formed, while constraining the gain ripple.

The characteristics of the desired null pattern determine which null synthesis method should be used. When only a low gain ripple is required, the orthogonal projection method with a window function can be used. On the other hand, the objective weighting method can be used to obtain a narrow null when a higher gain ripple is tolerable. The resulting null depth for these two methods will depend on the number of elements as well as the inter-element spacing. The constrained optimisation method can be used to control both the null depth and the ripple, while obtaining a similar null width to that resulting from using the objective weighting method.

The influence of variation in the antenna element configuration on the remaining unconstrained pattern characteristics, while controlling certain null pattern characteristics, was studied. The null pattern characteristics for the axial polarisation were only slightly influenced by a change in the substrate height. The resulting ripple and null width for both polarisations were influenced by a change in the dielectric constant, when the null depth was constrained. The degree to which the unconstrained characteristics of the resulting null pattern changed as the null position was varied, also depended on the polarisation. The sensitivity of the resulting null pattern characteristics to a change in the desired null position or a change in an antenna element characteristic, can be minimised by a careful selection of the element pattern.

5.2 Implementation of cylindrical microstrip patch arrays

A study on the implementation of the cylindrical microstrip patch array was also done. The simulation of the cylindrical microstrip patch element was discussed and both simulated and measured results were compared. The patch antenna elements were simulated and designed using a Finite Difference Time Domain (FDTD) software package [101]. The resulting reflection coefficient characteristics differed from the desired characteristics due to approximations made in the simulation of the cylindrical patch elements and due to the manufacturing tolerances. For both polarisations, the simulated and measured element radiation patterns compared well within the area of the main beam and differed slightly for the rest of the radiation pattern.

The nulls introduced in the beam patterns of linear monopole arrays were found to be shifted or filled due to mutual coupling [74]. Abele [53] studied the effect of the mutual coupling on the null pattern of a cylindrical dipole array and concluded that the coupling needed to be compensated for to prevent distortion of the null pattern characteristics. In this study, the extent to which the mutual coupling affected the characteristics of both linear and cylindrical narrowband patch arrays, was investigated.

Firstly, the extent to which the mutual coupling affected the reflection coefficient and bandwidth at the input port of a narrowband linear microstrip array, was studied. This investigation was conducted in order to study the improvement in the bandwidth due to the use of a mutual coupling compensation technique. For a narrowband linear microstrip array, both the minimum of the reflection coefficient at the input port of the feeding network and the resonant frequency were influenced by the mutual coupling. For a horizontally polarised array with $d_\phi = 0.5\lambda_0$, a coupling factor of -10.4 dB altered the resonant frequency to such an extent that the active bandwidth fell outside the desired bandwidth of the array. The resonant frequency and bandwidth were less affected for a vertically polarised array due to the smaller magnitude of the coupling ($<$ -16.2 dB).

For the cylindrical microstrip patch arrays, the influence of the mutual coupling on the null patterns was also studied. It was seen that the gain ripple in the omni-region, as well as the null depth, width and position were changed by the coupling. The null positions and null widths were more significantly affected for the circumferential polarisation. For a circumferentially polarised array with $d_\phi = 0.5\lambda_0$, the null position changed by 3.25° and the null width increased by 7.8°. For small inter-element spacing, the radiation patterns of axially polarised arrays were less affected by the coupling. For large inter-element spacing ($d_\phi = 0.7\lambda_0$), the gain ripple in the omni-region changed significantly for both polarisations due to the mutual coupling. The gain ripple changed from 1 dB to 4.63 dB and 2.55 dB for the circumferential and axial polarisations, respectively.

From this study, it was evident that the null patterns of the cylindrical patch arrays were affected by the mutual coupling. To match the desired and active characteristics of the patch arrays, a mutual coupling compensation technique was utilised. Chen [88,89] varied the lengths and radii of the dipoles in linear and planar arrays to obtain the desired radiation patterns as well as equal driving impedances for the dipoles. For the patch antenna elements, the lengths and feed positions were varied to provide matched and equal driving impedances for all the antenna elements given a required set of excitations. The lengths and feed positions at which the driving impedances of all the patches were equal to 50Ω, were determined.

For an axially polarised cylindrical array, suitable lengths and feed-positions were found for all the inter-elements spacing that were studied and null depths up to 40 dB. For small inter-element spacing, the higher mutual coupling in the circumferentially polarised patch arrays restricted the null depth for which the coupling could be compensated for using the described technique. For the smallest inter-element spacing studied ($d_\phi = 0.5\lambda_0$), the maximum null depth for which the coupling could be compensated for was found to be 10 dB. As the inter-element spacing was increased, the possible null depth could be increased while still being able to correct the driving impedances by finding suitable lengths and feed positions within the available variable space.

In the first test case, the compensation technique improved the resonant frequency of a linear microstrip patch array ($N = 4$, $d_\phi = 0.5\lambda_0$) to be within 0.1% of the desired frequency and the measured bandwidth (for VSWR < 1.5) of the array was increased significantly from 2.3% to 3.9%.

For the second test case, an axially polarised cylindrical patch array was used with $N = 10$ and $d_\phi = 0.5\lambda_0$. The lengths and feed positions of the antenna elements were varied to correct the driving impedances for the desired set of element excitations. Over the element bandwidth of 3.7% for VSWR < 2, the resulting null widths and depths compared well to the null widths and depths of the desired null pattern after applying the compensation technique. The null positions were also improved over the whole bandwidth. The resulting gain ripple at the lowest and highest frequency differed by only 0.08 dB for the compensated array. This was an improvement on the ripple variation of 0.87 dB over the bandwidth for the uncompensated array.

The configuration of a cylindrical microstrip patch array thus plays an important role in the null pattern synthesis. The patch antenna element configuration, the inter-element spacing and the number of elements should all be chosen carefully in order to obtain the desired null pattern as well as the specified driving impedances. The magnitude of the mutual coupling will also influence the choice of the inter-element spacing with the aim of obtaining the desired pattern while compensating for the coupling.

The effect of the mutual coupling on the null pattern was not severe for the cylindrical microstrip patch array used in the test case. The null depth decreased by 3.4 dB and the null width increased by 2.9°, while the ripple and null position varied little. If the changes in the null pattern characteristics are not severe and it can be tolerated by the system which the antenna is integral to, the mutual coupling compensation is not needed. This can be an advantage, especially when the array is used in an adaptive system.