
Conclusions and Future Research

5.1 GENERAL CONCLUSIONS

The principal contributions of this study include the development of a new capacitive feeding mechanism for wideband probe-fed microstrip patch antennas as well as the implementation of a spectral-domain moment-method formulation for the efficient analysis of large, finite arrays of these elements. Such antenna configurations are very useful in the wireless communications industry, but extremely difficult to analyse with commercially available software.

The new feeding mechanism for wideband probe-fed microstrip patch antennas consists of a small probe-fed capacitor patch that is situated next to the resonant patch, both patches residing on the same substrate layer. The gap between the capacitor patch and the resonant patch effectively acts as a series capacitor, thereby overcoming the inductance usually associated with probe-fed microstrip patch antennas on thick substrates. It has been demonstrated, that by using such a feeding mechanism, impedance bandwidths in the order of 32% can be achieved for a voltage standing-wave ratio (VSWR) of 2:1, while 25% can be achieved for a VSWR of 1.5:1.¹ These are better than the 10% to 15% bandwidths that are required for wireless communications systems such as the Global System for Mobile (GSM) Communications and the Universal Mobile Telecommunications System (UMTS). A major advantage of the new feeding mechanism is that only a single substrate is required to support the antenna. This implies cost savings when compared to other approaches, as well as simplified manufacturing techniques and light weight.

¹ These impedance bandwidths were achieved with a specific substrate and at a specific operating frequency. It might be possible to increase these bandwidths with other substrate materials and at other operating frequencies.

The design of the new antenna element is very straightforward. The substrate thickness is determined by the required impedance bandwidth. Thereafter, the size of the resonant element can be found by using conventional methods. The characterisation of the new antenna elements has shown that there are basically only two parameters that have to be altered in order to match the input impedance of the antenna to that of the feed network. These are the size of the capacitor patch and the size of the gap between the capacitor patch and the resonant patch. The size of the capacitor patch mainly determines the reactive part of the input impedance, while the size of the gap mainly determines the resistive part of the input impedance. Results for both rectangular and circular capacitor patches have been shown. It has also been demonstrated, both through numerical modelling and measurements, how the new feeding mechanism can be applied to rectangular, circular and annular-ring elements.

As is the case with other probe-fed microstrip patch antennas on thick substrates, the new antenna element also has a slightly squinted radiation pattern in the E -plane and slightly higher cross-polarisation levels in the H -plane. However, these can be rectified by using symmetric probes or by using proper orientation of the elements in an array configuration. Numerical modelling and experimental measurements have shown how the antenna element can be used in various antenna array configurations. These include vertically polarised, horizontally polarised and slant-polarised arrays. It has also been shown that acceptable cross-polarisation levels and port-decoupling can be achieved for dual-polarised arrays.

For the numerical modelling of the new antenna element, as well as arrays that are based on it, a SDMM formulation, which can handle any number of substrate layers on an infinite ground plane, has been implemented. The formulation is based on a unique combination of entire-domain and subdomain basis functions, leading to considerable savings in computer-memory requirements when compared to commercial codes (both in the spectral and spatial domains) that normally only use subdomain basis functions. With this formulation, the electric current density on the resonant patches is modelled with a set of entire-domain modes, that on the rectangular capacitor patches with rectangular rooftop basis functions and that on the probes with piecewise-sinusoidal basis functions. A circular attachment mode is used to model the electric current density at the probe-to-patch junctions. In addition, all of the electric current density on the circular capacitor patches can be modelled with only the attachment mode. This makes antenna elements with circular capacitor patches much more efficient to analyse. Examples have been shown where the savings in terms of computer memory is more than 2500 times when compared to some commercial moment-method (MM) codes. This savings can even become larger when larger antenna arrays are analysed. In terms of accuracy, the numerical formulation compares well with other commercial codes.

Commercial SDMM codes are normally based on an underlying rectangular grid, implying that the modelled structure often has to be modified in order to fit into the grid. This new model allows for arbitrary-sized basis functions that can also have an arbitrary orientation with respect to each

other. There is therefore no need to modify the geometry of the actual structure.

A very important type of basis function, which is required when a probe is connected to a microstrip patch, is the so-called attachment mode. In the literature, various attachment modes have been proposed for the SDMM, but it was not clear as to what the limitations of each one are. Some of these modes have been studied in various situations, resulting in a better understanding of where they are applicable. The circular attachment mode has also been extended for a more accurate description of the electric current density on small circular probe-fed capacitor patches.

One of the difficulties associated with the SDMM, is the highly oscillating nature of the interaction integrands for basis and testing functions that are widely separated. A recent publication dealt with this issue by proposing a new integration path in the complex plane over which the integrand decays exponentially. However, this method becomes less efficient as the basis and testing functions move closer to each other, even more so for thick substrates. This method has been extended and can now also be used in situations where the basis and testing functions are relatively close to each other on a relatively thick substrate. The conditions under which this method is valid, have also been extended.

When using the MM, the interactions between all basis and testing functions have to be calculated. However, depending on the implementation, there are often identical interactions that have to be calculated repeatedly. On a rectangular grid, these duplicate entries can easily be identified and eliminated, but becomes much more difficult with a mixture of lower-order and higher-order basis functions that are arbitrarily orientated. Special algorithms have been developed to deal with such a mixture of basis and testing functions, and proves to speed up the solution significantly.

One drawback of the SDMM, is that numerical integration is still required to evaluate each of the entries of the interaction matrix. It makes this implementation of the SDMM slower than commercial codes, where the entries are evaluated in the spatial domain and where lookup tables and other methods can be used to speed up the evaluation of the Green's function. However, due to the fact that this formulation uses far fewer basis functions, the difference in computational time is only observed for the analysis of single antenna elements and small arrays. For larger antenna arrays, the computational times are comparable, while for very large arrays, this implementation of the SDMM will be quicker. Another drawback of the SDMM, when compared to commercial codes, is that it is limited to specific geometries (it has after all been developed for a specific application). Some experience is also required in terms of the entire-domain basis functions that should be used on the resonant patches.

5.2 FUTURE RESEARCH

As is the case with all research, there are always more aspects that can be investigated than what is practically possible. Here also, there are some aspects of both the new antenna and the numerical

formulation that can be extended.

Although the new antenna elements have been characterised to some extent, it would be useful to have more comprehensive guidelines to design such antenna elements. This should include geometrical parameters as well as the optimum choice of material properties, especially dielectric constants and substrate thicknesses. The SDMM, which has been implemented, can be used to analyse various configurations, while the results can be used to build up a database. The design guidelines can then be extracted from such a database. Optimisation techniques, such as genetic algorithms [199–201], can also be useful.

It has been shown by other authors that superstrates can have some advantageous effects on the performance of microstrip patch antennas, such as widening of the impedance bandwidth [202–205]. Also, in practice, most antennas are covered by a radome for protection. It would therefore be interesting to study the effects of superstrates when used in conjunction with the new antenna element and associated antenna arrays. This can of course be handled most easily with the current numerical formulation as it already caters for an arbitrary number of substrate/superstrate layers.

The size of the new antenna element can further be reduced by reducing the length of the rectangular resonant patch to one quarter of a wavelength and shorting the side opposite to the capacitor patch. Such an element could be useful in applications where really small antennas with wide bandwidth are required. However, from a modelling point of view, it would not be possible to use the current formulation. The analysis would require vertical current strips and it would most likely not be possible to use entire-domain basis functions on the quarter-wave patch.

Some applications, especially space applications, require the use of circular polarisation. There are various ways to obtain circular polarisation with conventional probe-fed microstrip patch antennas. It can be done with one probe, two probes, or by using sequentially rotated patches. It should be possible to apply the same ideas to the new antenna element.

It should be a fairly straightforward process to extend the numerical formulation so that circular and annular-ring resonant patches can also be included. It is possible to model the electric current density on such shapes with entire-domain basis functions of which the Fourier transforms are already available in the literature [28, 51, 128, 206, 207]. The analysis of antennas with these patch shapes might even prove to be more efficient as it might be possible to use the separation of variables while evaluating the integrals associated with the interaction-matrix entries. The integration limits and integration intervals for interaction-matrix entries that contain these functions, would have to be determined as well.

While the numerical integration, associated with the interaction between a basis function and a testing function, has already been optimised, there is a specific case where all the integration

strategies that have been implemented, are still inefficient. This is for lateral overlap between a small basis/testing function, such as a subdomain function, and a large testing/basis function, such as an entire-domain function. This can, for example, occur when the gap between the two functions is very small and the functions are not aligned, or when the two functions are on separate layers and overlap laterally.² In such cases, the centres of the two functions can still be laterally separated to such an extent, that the integrand associate with the interaction between the two functions, become very oscillatory. Due to the fact that the functions overlap, the integration strategy for laterally separated functions cannot be used, while the integration strategy for overlapping functions become very inefficient. The development of an integration strategy that can handle such situations, would be very useful.

The modelling of wideband antennas often require the analysis to be performed over a large number of frequency points. It is possible to reduce the computational time by analysing the antenna at only a few selected frequency points and to then use interpolation in some intelligent way to find the response at other frequency points. One such a technique uses rational functions to interpolate the response [208, 209], while another uses interpolation of the interaction-matrix entries [210]. Such techniques should also prove to be useful for the numerical formulation that has been implemented here.

² Although overlapping large and small basis/testing functions on separate layers are not required for the modelling of the new antenna element, the numerical formulation could also be used to handle other configurations that require such overlapping basis/testing functions. An example is stacked patches.