CHAPTER 1

Introduction

1.1 BACKGROUND AND MOTIVATION

During recent years, there has been an enormous growth in the wireless communications industry. The deployment of systems such as cellular telephone networks, wireless local loop networks and wireless local area networks, is rapidly evolving worldwide. As more and more people use these services, network operators are constantly forced to optimise their networks so that the maximum amount of capacity, together with quality coverage, can be squeezed out of these networks. The field of antenna engineering is of course central to all wireless technologies and plays a significant role in the successful deployment and optimisation of such systems. As such, the growing demand for wireless communications, has stimulated extensive research in order to find new solutions to problems in antenna engineering.

With the advances in wireless communications technologies and the associated proliferation of base stations throughout major cities and much of the countryside, a number of requirements are imposed on the antennas that are used. From a technological point of view, wireless communications antennas should be relatively cheap and easy to manufacture, they should be lightweight and they should be robust. From an environmental point of view, the antennas should have a minimum impact. As such, these antennas should have a low profile and should be as compact as possible. This of course also goes for handset antennas, where the size of such devices is constantly shrinking.

One type of antenna that fulfills these requirements very well, is the microstrip antenna. These antennas operate in the microwave frequency range and are widely used on base stations as well as handsets. They come in a variety of configurations and have been the topic of what is currently

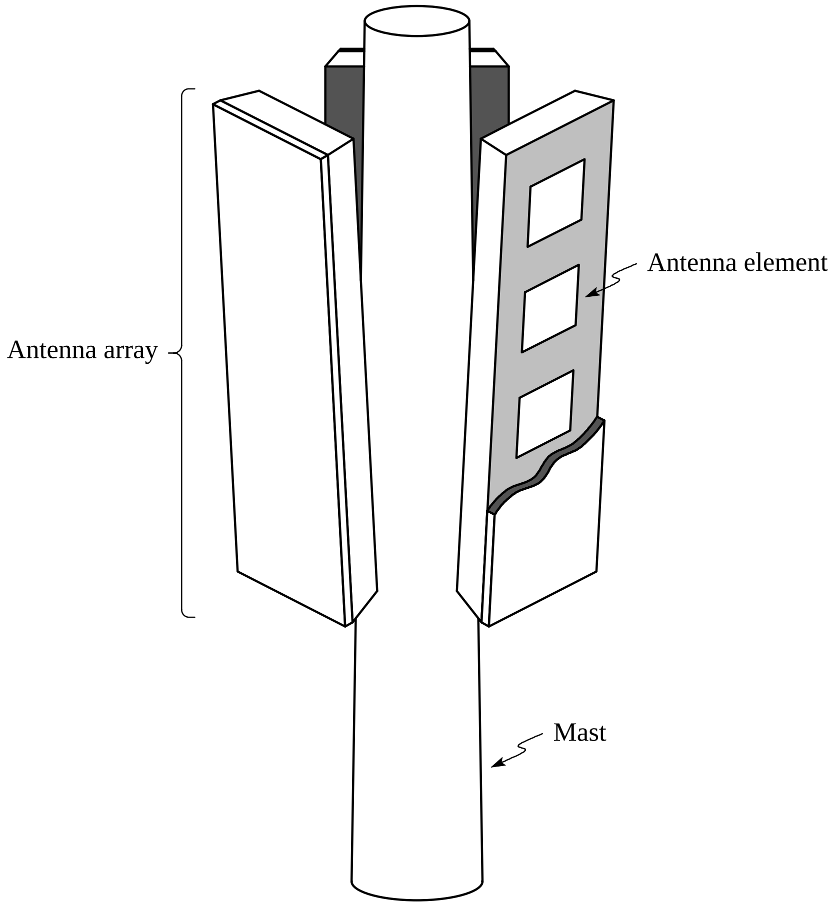

Figure 1.1 Cellular base-station antennas. Each antenna array comprises of a number of antenna elements.

probably the most active field in antenna research and development. In one of its most basic forms, a microstrip antenna is comprised of a metal patch that is supported above a larger ground plane. It is usually manufactured by printing the patch on a thin microwave substrate. This configuration is commonly known as the microstrip patch antenna. Microstrip patches are often used as single-element antennas, but are also very suitable for use within antenna arrays. Figure 1.1 shows a typical example of how they can be used in directional base-station antennas.

Rectangular and circular patches are most common, but any shape that possesses a reasonably well-defined resonant mode can be used [1]. These include, for example, annular rings, ellipses and triangles. The patch is a resonant element and therefore one of its dimensions must be approximately one half of the guided wavelength in the presence of the dielectric substrate. There are four fundamental techniques to feed or excite the patch [2–4]. These are shown in Figure1.2 and include the probe feed, the microstrip-line feed, the aperture-coupled feed and the proximity-coupled feed.

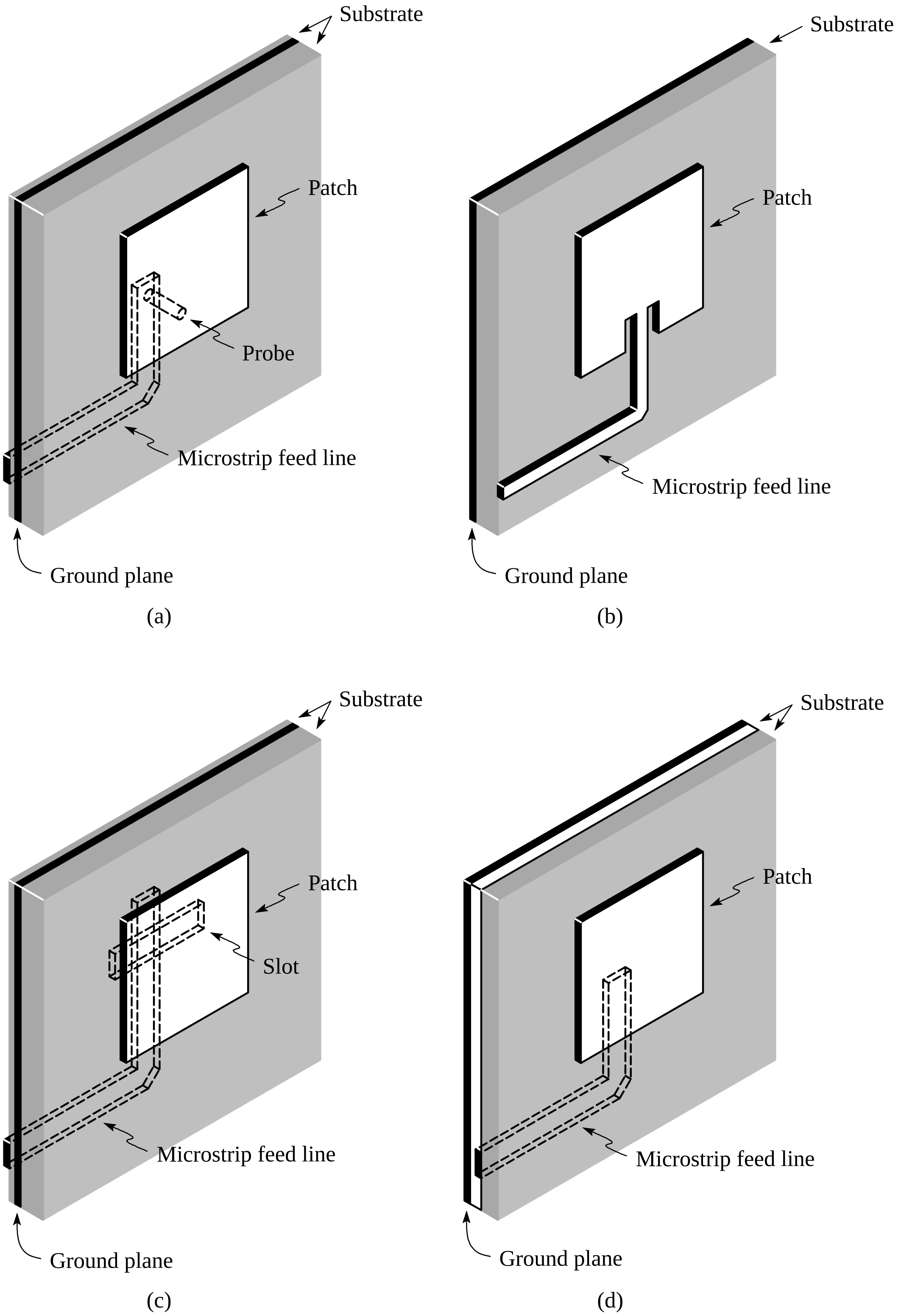

Figure 1.2 Typical feeding techniques for microstrip patch antennas. (a) Probe feed. (b) Microstrip-line feed. (c) Aperture-coupled feed. (d) Proximity-coupled feed.

The probe feed, as shown in Figure 1.2(a), is constructed by extending a probe through the ground plane and connecting it to the patch, typically by soldering it. If the patch is part of an antenna array, the feed network can be printed on a substrate behind the ground plane. In such a case, the other end of the probe will typically be soldered to a microstrip line that forms part of the feed network. In the case of single-element antennas, the probe is usually the inner conductor of a coaxial cable of which the outer conductor is soldered to the ground plane. The input impedance is controlled by the position of the probe-to-patch connection point. The microstrip-line feed, as shown in Figure 1.2(b), consists of a microstrip line that is connected to one of the edges of the patch. The position of the connection point is also used to control the input impedance. As shown in Figure 1.2(b), this can be achieved by insetting the microstrip line into the surface of the patch. With the aperture-coupled feed, as shown in Figure 1.2(c), the microstrip feed line and the patch are separated by a ground plane. Coupling between the feed line and the patch is then achieved via a small slot in the ground plane. Unlike the aperture-coupled feed, the proximity-coupled feed, as shown in Figure 1.2(d), has a microstrip feed line that is printed on a substrate layer between the ground plane and the patch. In this case, power from the feed line is electromagnetically coupled to the patch.

Each one of the feeding techniques has its own advantages and disadvantages. However, the probe feed has a number of characteristics that make it very suitable for applications in the wireless communications field. Due to the fact that the probe is connected directly to the patch, the antenna structure is quite robust. The probe feed is also less prone to alignment errors, which can significantly affect the performance of aperture-coupled and proximity-coupled feeds. Due to the fact that the feed network is separated from the patch, there is less spurious radiation from the feed network as compared to that of the microstrip-line feed and the proximity-coupled feed. A somewhat related disadvantage of the aperture-coupled patch, is that it can exhibit unwanted backward radiation through the slot in the ground plane. The probe feed also has the advantage that it can be driven directly via a coaxial cable, thereby avoiding the use of an additional substrate layer to support the feed line.

The main drawback associated with microstrip patch antennas in general, be they probe-fed or not, is that they inherently have a very narrow impedance bandwidth[1] (due to their multilayered configuration, aperture-coupled feeds and proximity-coupled feeds do tend to have a slightly wider bandwidth than probe feeds and microstrip-line feeds). In most cases, the impedance bandwidth is not wide enough to handle the requirements of modern wireless communications systems. The narrow impedance bandwidth of microstrip patch antennas can be ascribed to the thin substrates that are normally used to separate the patch and the ground plane. The general performance trends of a microstrip patch antenna are illustrated in Figure 1.3 [2–4]. Here, Figure 1.3(a) shows the typical trend for impedance bandwidth versus substrate thickness, as a function of the substrate's

[1] Impedance bandwidth refers to the frequency range over which the antenna can be matched to its feed line. It is usually specified in terms of the acceptable return loss or voltage standing-wave ratio at the antenna port.

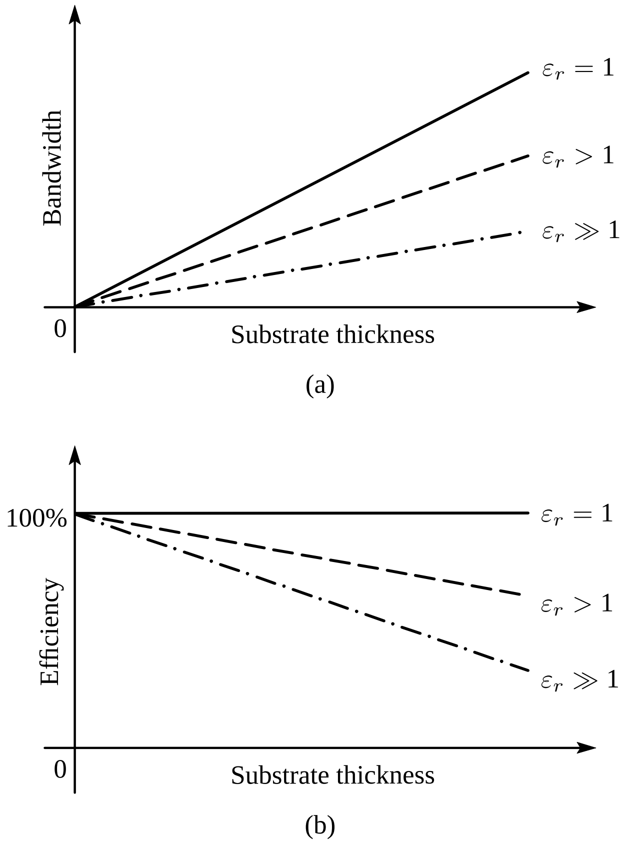

Figure 1.3 Illustrative performance trends of a microstrip patch antenna. (a) Impedance bandwidth. (b) Surface-wave efficiency.

dielectric constant, while Figure 1.3(b) shows the typical trend for surface-wave efficiency versus substrate thickness, also as a function of the substrate's dielectric constant. From these it can be seen that, in order to increase the bandwidth, the substrate thickness has to be increased, while the dielectric constant has to be kept as low as possible. A low dielectric constant is also required to keep surface-wave losses as low as possible. Therefore, in order to obtain a wideband microstrip patch antenna with good surface-wave efficiency, the performance trends of Figure 1.3 point to a thick substrate with a very low dielectric constant.

While a thick substrate does increase the impedance bandwidth of microstrip patch antennas, it also introduces a further complication for microstrip patch antennas with probe feeds. For thin substrates, the input impedance at the resonant frequency is basically purely resistive, but as the substrate thickness is increased, the input impedance becomes more inductive [4–7]. This is illustrated in Figure 1.4, where the input impedance is given by $Z_{\text{in}} = R_{\text{in}} + jX_{\text{in}}$ at the resonant frequency f_0. In order to offset the inductive component of the input impedance, an alternative feeding mechanism to the direct probe feed is required.

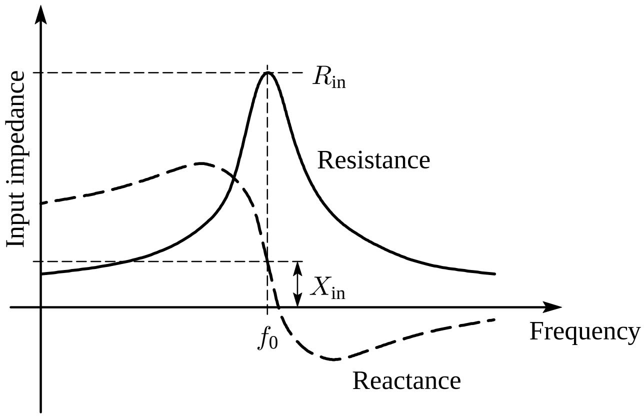

Figure 1.4 Illustrative input impedance of a probe-fed microstrip patch antenna on a thick substrate.

To this date, various feeding mechanisms, as well as various other approaches to enhance the impedance bandwidth of probe-fed microstrip patch antennas, have been suggested and implemented. These, for example, include wideband impedance-matching networks, edge-coupled patches, stacked patches, shaped probes, capacitive coupling and slotted patches. However, not all of these solutions fulfill the requirements that are imposed by modern-day wireless communications systems. Some of the solutions are not suitable for array applications, some require multiple substrate layers, some are very complex to design, while others are very sensitive to alignment errors and manufacturing tolerances. As such, the research into wideband probe-fed microstrip patch antennas, which are suitable for modern-day wireless communications systems, is still a very relevant topic. The number of publications that still appear on this topic also confirms that it is indeed the case.

Another area of research, which is closely linked to advances in antenna development, is the field of computational electromagnetics. As antennas become more complex, the use of simple analytical modelling techniques is not sufficient anymore. The use of more sophisticated numerical methods, such as full-wave modelling techniques, has therefore become inevitable. However, with these methods, the modelling of complex antenna configurations, and especially large antenna arrays, can become very computationally expensive and can easily exceed the capabilities of most personal computers. As such, the search for techniques that can reduce the computational complexity of these methods, is currently a very important research area and much progress has indeed been made during recent years.

Most of the research into new antenna elements and numerical modelling techniques has been performed independently from one another. This has resulted in general-purpose numerical modelling techniques, which is good per se, but which can require extensive computational resources for modelling electrically large antennas. The aim of this thesis is therefore firstly the development of a new wideband probe-fed microstrip antenna element, which on the one hand, fulfills the requirements of modern-day wireless communication systems and improves on the shortcomings of previous approaches, but which on the other hand, also lends itself to more efficient numerical modelling techniques. The second aim of the thesis is then the formulation and implementation of a numerical modelling technique that can be used for the analysis and design of such antennas without resorting to excessive computational resources. In the next section, the specific objectives and scope of the study will be formulated in more detail.

1.2 OBJECTIVES AND SCOPE

As mentioned in the previous paragraph, the focus of this study is in two main areas. These are the development of new wideband probe-fed microstrip patch antenna elements and arrays, as well as the development of numerical modelling techniques for the efficient analysis and design of such antennas. The specific objectives and scope of the research are described in the bullets that follow.

- The first objective of this research is the development of a feeding mechanism for wideband probe-fed microstrip patch antenna elements. Modern wireless communication systems, such as the Global System for Mobile (GSM) Communications and the Universal Mobile Telecommunications System (UMTS), typically require bandwidths of approximately 10% to 15%. For this research, the base station antennas are of particular interest and therefore the new antenna elements should be suitable for use within various array configurations, while still retaining the benefits of low cost, light weight, low profile, as well as ease of design and manufacture. As microwave substrates can be relatively expensive for large arrays, it would be beneficial to minimise the number of substrate layers. Furthermore, in order to enhance the efficiency of the numerical modelling, the radiating patch elements will be restricted to rectangular shapes. The scope of this study will also be limited to single-band antenna elements only.

- An objective that follows from the previous bullet, is to verify the performance of the new antenna element, to characterise it, and to show how it can be used in various applications. This will be achieved through numerical modelling as well as through actual experimental measurements.

- Another major objective of this study is the formulation and implementation of an efficient numerical modelling technique, which can be used for the analysis and design of antenna elements and arrays that are based on the new antenna element. Here, the focus is primarily on minimising the amount of computer memory that is required. This is very important for the analysis of large antenna arrays. In terms of accuracy, the numerical model should compare well to commercial codes. It should handle multiple substrate layers as well as planar and vertical currents.[2] The analysis of arbitrarily-orientated antenna elements should

[2] Vertical currents are required to model the probe feeds, while horizontal currents are confined to specific planar layers. This is commonly referred to as a so-called 2.5D formulation.

also be possible (i.e. it should not be restricted to configurations where the antenna elements are all aligned to a rectangular grid). The scope of the numerical model will be limited to the antenna elements only. Feed networks can be implemented in many ways and can usually be designed effectively with existing modelling techniques. Also, for probe-fed antennas, the feed network is well isolated from the antenna elements and therefore any coupling between the feed network and the antenna elements can be ignored.

- Finally, an important objective is the validation of the numerical model as well as various examples to illustrate its performance and benefits. For this purpose, the results of the numerical formulation will be compared to published results, measurements, as well as the simulation results of two commercial codes.

1.3 ORIGINAL CONTRIBUTIONS

This study has resulted in a number of original contributions, of which some have already been published by the author [8–14]. In summary, 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 detailed contributions are described in the bullets that follow.

- A novel feeding mechanism has been developed for probe-fed microstrip patch antennas on thick substrates, which, in principle, can be used with any shape of radiating element. As shown in Figure 1.5, the feeding mechanism consists of a small probe-fed patch that is capacitively coupled to the radiating element, thereby overcoming the inductance usually associated with a probe in a thick substrate. It has been demonstrated, both through numerical modelling and measurements, how this concept can be applied to rectangular as well as circular and annular-ring radiating elements. These elements have all been characterised and it turns out that this feeding mechanism is very easy to design and optimise. It has also been shown how these elements can be used in various array configurations.

- A new full-wave model, based on the spectral-domain moment-method (SDMM), has been developed to analyse these structures in multilayered substrates. This model is based on a unique combination of subdomain and entire-domain 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.

- 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.

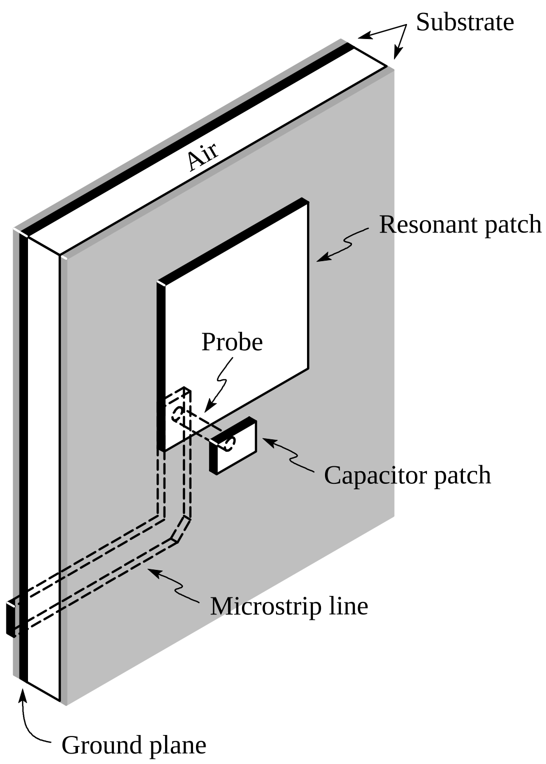

Figure 1.5 New wideband microstrip patch antenna with the capacitive feed probe.

- 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 subdomain and entire-domain 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. During this study, the 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 refined.

- When using the moment method (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 functions and proves to speed up the solution significantly.

1.4 OVERVIEW OF THE THESIS

This chapter presented some background information on microstrip patch antennas and the various feeding techniques that can be used. It was pointed out why the probe feed is of particular interest for wireless communications systems and what the challenges are when wideband operation of these antennas is required. The shortcomings of existing approaches, in terms of antenna elements and modelling techniques, were also briefly pointed out. With these in mind, the main objectives and scope of the study were formulated. In short, it includes the development of new wideband probe-fed microstrip antenna elements and arrays, as well as the development of numerical modelling techniques for the efficient analysis and design of such antennas. The original contributions that followed, were also summarised. A short overview of the remaining chapters will now follow.

Chapter 2 starts off by presenting an overview of various techniques that have been used thus far for the bandwidth-enhancement of probe-fed microstrip patch antennas. The performance as well as the advantages and disadvantages of the most practical approaches is also discussed. This is followed by presenting the new microstrip patch antenna element with the capacitive feed probe. Chapter 2 then also gives an overview of various modelling techniques that can be used for the analysis and design of probe-fed microstrip patch antennas. These range from simple approximate methods to advanced full-wave methods. The strengths and weaknesses of each method is also addressed. Finally, the chapter is concluded by an overview of the formulation that was implemented for the purposes of this study. The formulation is based on the SDMM.

Chapter 3 deals with the implementation of the SDMM formulation. It starts off with a general overview of the MM and shows how it can be formulated in the spectral domain. The Green's function for planarly multilayered media is discussed in detail, as are the various basis functions that were used. Various numerical integration strategies were implemented. These, together with algorithms that were implemented to minimise duplicate calculations, are also presented with the necessary detail. In short, Chapter 3 covers all the computational aspects of the formulation that was implemented. These also include the evaluation of the different network parameters and far fields.

Chapter 4 contains all the numerical and experimental results. It starts off with a validation of the SDMM formulation that was implemented. This is followed by a characterisation of the new antenna element in order to determine the effect of the various geometrical parameters. A number of applications are also presented. These include vertically and horizontally polarised arrays, as well as $\pm 45^\circ$ slant-polarised arrays. Finally, it is shown how the new feeding mechanism can be used for microstrip patches where the resonant patch is not necessarily rectangular in shape.

Chapter 5 contains general conclusions regarding this study and concludes the thesis with some recommendations that can be considered for future work.