Adaptive A Design for Wireless Communication Systems

Nurul Hazlina Noordin

A thesis submitted for the Degree of Doctor Philosophy

The University of Edinburgh

2013

Abstract

Adaptive array antennas use has been limited to non-commercial applications due to their high cost and hardware complexity. The implementation cost of adaptive array antennas can be kept to a minimum by using cost effective antennas, reducing the number of elements in the array and implementing efficient beamforming techniques. This thesis presents techniques for the design of adaptive array antennas which will enable their cost effective implementation in wireless communication systems. The techniques are investigated from three perspectives, namely, reconfigurable antenna design, wide scan array design and single-port beamforming technique.

A novel single-feed polarisation reconfigurable antenna design is proposed in the first stage of this study. Different polarisation states, namely, linear polarisation (LP), left-hand circular polarisation (LHCP) and right-hand circular polarisation (RHCP), are achieved by perturbing the shape of the main radiating structure of the antenna. The proposed antenna exhibits good axial ratio (< 3 dB at 2.4 GHz) and has high radiation efficiency in both polarisation modes (91.5 % - LHCP and 86.9 % - RHCP). With a compact single feeding structure, the antenna is suitable for implementation in wireless communication devices.

The second stage of the study presents the design procedure of wide scan adaptive array antennas with reduced number of elements. Adaptive array antennas with limited number of elements have limited scanning range, reduced angular scanning resolution and high sidelobe levels. To date, design synthesis of adaptive array antennas has been targeted on arrays with a large number of elements. This thesis presents a comprehensive analysis of adaptive array antennas with less than 10 elements. Different array configurations are analysed and various array design parameters such as number of elements, separation between elements and orientation of the elements are analysed in terms of their 3 dB scan range. The proposed array, the 3-faceted array, achieves a scanning range up to ±70°, which is higher than ±56° obtained from the Uniform Linear Array. The faceted arrays are then evaluated in the context of adaptive beamforming properties. It was shown that the 3-faceted array is suitable for adaptive array applications in wireless communication systems as it achieves the highest directivity compared to other faceted structures. The 3-faceted array is then synthesised for low sidelobe level. Phase correction together with amplitude tapering technique is applied to the 3-faceted array. The use of conventional and tuneable windowing techniques on the 3-faceted array is also analysed.

The final stage of the study investigates beamforming techniques for the adaptive array antenna. In the first part, beamforming algorithms using different performance criteria, which include maximum signal-to noise-ratio (SINR), minimum (mean-square Error) MSE and power minimisation, are evaluated. In the second part, single-port beamforming techniques are explored. In previous single-port beamforming methods, the spatial information of the signals is not fully recovered and this limits the use of conventional adaptive beamforming algorithms. In this thesis, a novel signal estimation technique using pseudo-inverse function for single-port beamforming is proposed.

The proposed polarisation reconfigurable antenna, the 3-faceted array antenna and the single-port beamforming technique achieve the required performance, which suggests the potential of adaptive array antennas to be deployed commercially, especially in wireless communication industry.

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

1D	1 Dimensional
2D	2 Dimensional
3D	3 Dimensional
ADC	Analog to Digital Converter
CMA	Constant Modulus Algorithm
DoA	Direction of Arrival
FIR	Finite Impulse Response
FM	Frequency-Modulated
FPGA	Field Programmable Gate Array
GA	Genetic Algorithm
HPBW	Half Power Beam Width
LHCP	Left-hand circularly polarised
LMS	Least Mean Squares
LNA	Low Noise Amplifier
LO	Local Oscillator
LPF	Low Pass Filter
MEMS	Microelectromechanical systems
mMSE	Minimum Mean-Square Error
MSE	Mean-Square Error
mSINR	Maximum Signal to Interference-plus-Noise Ratio
PM	Phase-Modulated
PSO	Particle Swarm Optimisation
RF	Radio Frequency
RHCP	Right-hand circularly polarised
RLS	Recursive Least Squares
SINR	Signal to Interference-plus-Noise Ratio
SLL	Sidelobe Level
SMI	Sample-Matrix-Inversion
SMILE	Spatial Multiplexing of Local Elements
SNOI	Signal not of interests
SNR	signal-to noise-ratio
SOI	Signal of interests
TDMA	Time Division Multiple Addressing
TPSW	Time Sequence Phase Weighting
UCA	Uniform Circular Array
UCCA	Uniform Cocentric Circular Array
UHA	Uniform Hexagonal Array
ULA	Uniform Linear Array
URA	Uniform Rectangular Array

Chapter 1

Introduction

1.1 Research Motivation

The widespread of wireless communication technology applications in our life has increased the requirement for efficient and reliable signal transmission. One way of achieving these requirements is by using smart antenna system.

Conventional antenna systems use standard omni-directional antenna that transmits signal in all directions including in the directions where the signal is not required. However, in real situations, the required signal is not necessarily coming from all directions. This results in inefficient signal transmission and power wastage. Hence, the idea of a smart antenna is introduced. A smart antenna produces highly directive radiation pattern that can be electronically controlled. This means the radiation of a smart antenna can be steered over the best signal path, and consequently reduce the power consumption of the wireless devices.

Smart antennas are divided into two categories, which are switched-beam antennas and adaptive array antennas [1-3]. A switched-beam antenna, as shown in Figure 1.1 (a), has a set of fixed radiation pattern and the appropriate pattern is selected based on the requirement of the wireless system. Although this technique exploits the spatial dimension of an antenna, the main beam sometimes could not point to the signal of interest (SOI), as shown in Figure 1.1 (b).

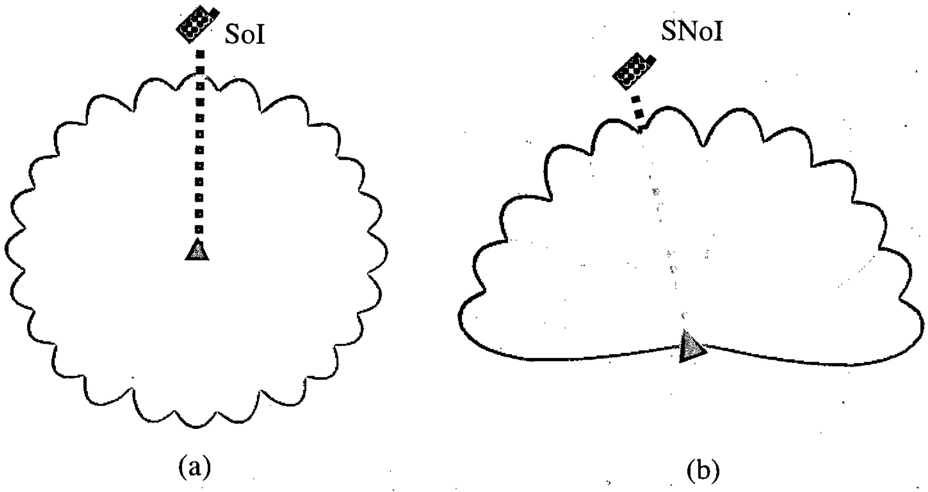

Figure 1.1: Switched-beam antenna, (a) pre-determined switching scheme, and (b) low resolution of the main beam.

On the other hand, the radiation pattern of an adaptive array antenna is controlled by adjusting the complex excitation of its elements and this allows the main beam to be arbitrarily placed, as illustrated in Figure 1.2 (a) [2, 3]. These excitations can also be manipulated so that the radiation points at the SOI while suppressing the radiation in the direction of signals not of interest (SNOI), as shown in Figure 1.2 (b). This feature is known as 'adaptive beamforming' and it allows the antenna to maximise its spatial usability [4-6].

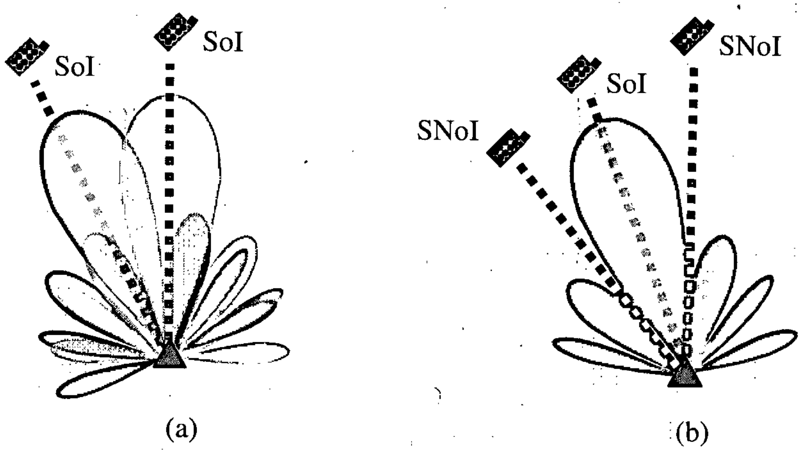

Figure 1.2: Adaptive array antenna, (a) arbitrary steering, and (b) adaptive beamforming.

However, despite their advantages, adaptive array antennas have not been commercially used due to implementation issues such as high cost and hardware complexity [4, 7-14]. Adaptive array antenna use has been limited to non-commercial applications such as ultrasound medical systems and military radar systems. To regain its commercial value and widespread usage in commercial wireless communication devices, the implementation cost of the adaptive array arrays must be kept to a minimum. This can be achieved by employing cost effective antennas, reducing the number of elements in the array and implementing an efficient beamforming technique.

1.2 Research Investigations

The main components of an adaptive array antenna are the antenna, the array and the signal processing unit. In order to reduce the cost of an adaptive array antenna for wireless communication applications, several challenges related to the components have to be addressed.

1.2.1 Adaptive Array Antenna Design Challenges

1.2.1.1 Antenna Design

One technique that can be used to design a cost-effective adaptive array is by employing reconfigurable antenna as the array elements. This is because, with the same radiating structure, the antenna has the ability to reconfigure its radiation properties such as the frequency, radiation pattern and polarisation [15-19]. The challenges associated with reconfigurable antenna designs include the reconfiguration mechanism and maintaining certain antenna characteristics while achieving the radiation diversities [18, 19]. Besides the configurable properties, the dimensions of the antenna also need to be considered, as only limited space is available in most communication devices.

This research investigates the design of a polarisation reconfigurable antenna for use in wireless communication systems. Polarisation reconfiguration is targeted because it enables frequency reuse and reduces the multi-path effects in the wireless communication channel [15, 20-22]. This is important in order to achieve high quality signal transmission. The aim is to develop a polarisation reconfigurable antenna that is compact, operates at 2.4 GHz and has directional radiation pattern.

1.2.1.2 Array Design

The geometry of an array, which is described by the arrangement of the elements in the array, influences the resulting radiation pattern of the adaptive array antenna. The array elements are fed in accordance with the desired amplitude and phase using suitable feeding network.

Generally, to avoid high coupling between elements in an antenna array, the ideal separation between two adjacent elements is 0.5 λ. Elements that are separated less than 0.5 λ have high coupling level and this consequently will distort the radiation pattern of the array [23, 24]. On the other hand, when the separations of the elements are more than 0.5 λ, the tendency for grating lobes to occur is high [25]. Grating lobe degrades the peak directivity of the array as the radiation power is transferred from the main beam to the lobes [26-28].

The cost of an adaptive array antenna is proportional to the number of the array elements. Hence, one technique of minimising the cost is by employing adaptive arrays with a small number of elements. However, adaptive array antennas with limited number of elements present their own challenges, which include limited scanning range, reduced angular scanning resolution and high sidelobe levels [29-31].

Array geometries consisting of fewer than 10 elements are investigated in this research. The aim is to develop an array with wide angle scanning abilities. Wide scan coverage is important, especially in wireless communication system, as the transmission link is not always within the boresight of an antenna. In the first stage, an adaptive array antenna with a wide scanning range is designed and developed. Various array configurations, such as uniform linear arrays and uniform circular arrays, are considered. In the second stage, these arrays are evaluated in the context of adaptive beamforming. The arrays are evaluated in environments that contain interference sources and beamforming algorithms are used to calculate the excitation weights of the array elements. Comparisons of the beamforming properties, such as the accuracy of the main beam and null placement, are then made. Finally, a technique to synthesise the wide scan array for low sidelobe level is explored.

1.2.1.3 Signal Processing Unit

The signal processing algorithm implemented in an adaptive array antenna contributes to its 'intelligence'. The signals induced on each element are analysed and processed so as to adjust the array radiation characteristic in order to adapt to the environment.

The attractive features of this intelligence are its ability to locate the desired signal, normally termed as directional-of-arrival (DoA), and adaptive beamforming. The DoA is calculated based on the time delays due to the impinging signals onto the adaptive array antenna. Once the DoA of a desired signal is estimated, beamforming algorithms are then used to optimise the complex excitations of the array elements.

Another technique for reducing the cost of an adaptive array antenna is by implementing a single-port signal processing architecture. In the single-port beamforming architecture, signals received at each antenna element are coherently combined using a power combiner before going through a single RF channel [32, 33]. A typical RF channel consists of a bandpass filter, a low noise amplifier, a mixer, a lowpass amplifier and an ADC. This means that the quantity of hardware required in a single-port beamformer is less than that of the multi-port beamformer. In addition, the single-port architecture consumes less power compared to the multi-port architecture as fewer hardware components are required. However, in return, due to the signal combination in the single-port architecture, the spatial and signal information from the array element is lost [34]. This information is essential when conventional beamforming algorithms are used in the adaptive array antenna.

This thesis investigates the single-port beamforming technique for use in wireless communication systems. In the first part of the investigation, beamforming algorithms using different performance criteria such as maximum signal to noise ratio (SINR), minimum mean square error (MSE) and power minimisation are explored. Then, the single-port beamforming algorithm is applied to the proposed wide scan array and the performance of the algorithm is evaluated.

The final development of the smart antenna system involves the design of power divider circuits and the estimation of Directional of Arrival (DoA) of a signal. However, these components are well-established as individual topics and are not covered in this thesis. This research focuses on the main structure of the adaptive array antenna in order to produce a low cost adaptive array antenna design. Design requirements of the adaptive array antenna for wireless communication system investigated in this thesis are tabulated in Table 1.1 and the research investigations of this thesis are summarised in Figure 1.3.

Table 1.1: Design Requirements for the Low Cost Adaptive Array Antenna for Wireless Communication Systems.

Components	**Design Requirements**	
Antenna Design	Operational Frequency	2.4 GHz
	Reconfiguration	Polarisation (LHCP /RHCP)
	Beamwidth	> 70° (Unidirectional)
Array Design	Operational Frequency	2.4 GHz
	Array Size	< 10 elements
	Scanning Range	> 60°
Beamforming Algorithm	Operational Frequency	2.4 GHz
	Array Size	< 10 elements
	Beamforming structure	Single-port

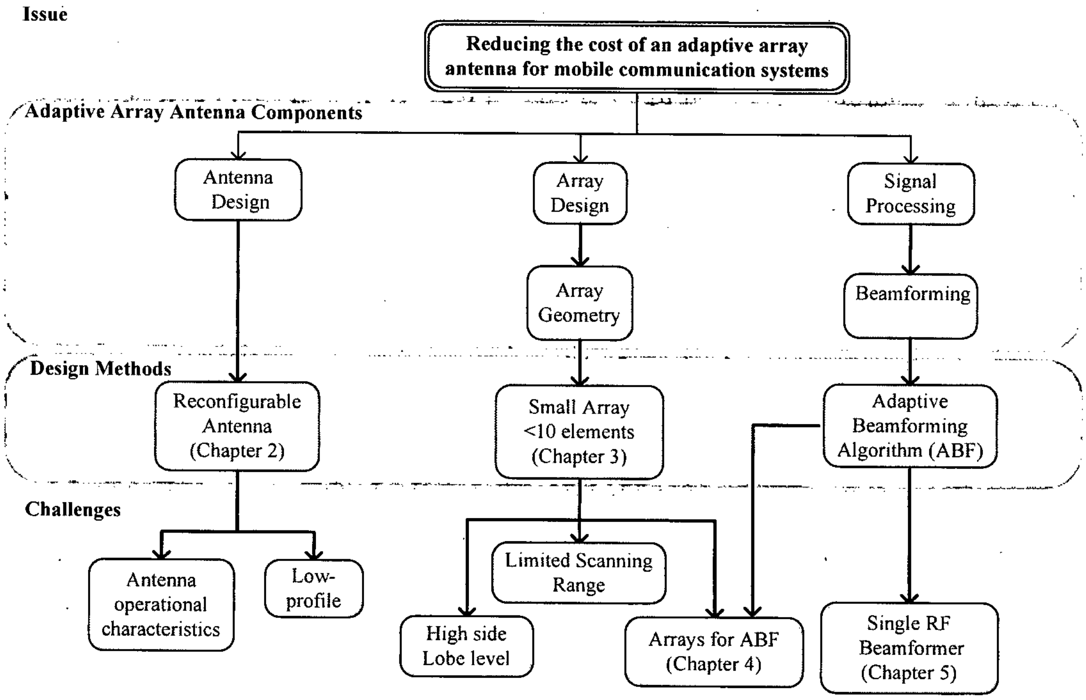

Figure 1.3: The structure of this research.

1.2.2 Research Objectives

The main objectives of this research are:

1. to design a polarisation reconfigurable antenna for wireless communication systems,
2. to design a wide scan range adaptive array antenna with a limited number of elements for wireless communication systems, and
3. to develop a signal estimation technique in a single-port beamforming architecture for wireless communication systems.

1.3 Publications Arising from This Research

Publications arising from this research are as follows:-

Peer-Reviewed Journal

2013

N. H. Noordin, Tughrul Arslan, Brian W. Flynn, Ahmet T. Erdogan, Ahmed O. El-Rayis, *Single-port Beamforming System for 3-faceted Phased Array Antenna*, IEEE Antenna and Wireless Propagation Letter, pp. 813-816, 2013.

2012

N. H. Noordin, T. Arslan, B. W. Flynn, and A. T. Erdogan, *Low-cost Antenna Array with Wide Scan Angle Property*, IET Microwaves, Antennas & Propagation, vol. 6, pp. 1717-1727, 2012.

Selected Refereed Conference

2013

N. H. Noordin, Tughrul Arslan, Brian W. Flynn, Ahmet T. Erdogan, *Faceted Arrays for Adaptive Beamforming Application* – accepted in Personal, Indoor and Mobile Radio Communications (PIMRC 2013).

N. H. Noordin, Tughrul Arslan, Brian W. Flynn, *Low Sidelobe Level Synthesis Technique for Faceted Arrays*, 7th European Conference on Antennas and Propagation (EuCAP 2013), Gothenburg, Sweden, April 8-12, 2013, pp. 592 - 596.

2012

N. H. Noordin, Nakul Haridas, Ahmed O. El-Rayis, Ahmet T. Erdogan, Tughrul Arslan, *Antenna Array with Wide Angle Scanning Properties*, 6th European Conference on Antennas and Propagation Prague (EuCAP 2012), Czech Republic, March 26-29, 2012, pp. 1636 - 1640.

N. H. Noordin, W. Zhou, Nakul Haridas, Ahmed O. El-Rayis, Ahmet T. Erdogan, Tughrul Arslan, *Single-Feed Polarization Reconfigurable Patch Antenna*, Antennas and Propagation Society International Symposium (APSURSI 2012), Chicago, Illinois, USA July 8-14, 2012, pp. 1 - 2.

N. H. Noordin, Ahmet T. Erdogan, Brian Flynn, Tughrul Arslan, *Compact Directional Patch Antenna with Slotted Ring for LTE Frequency Band*, Loughborough Antennas & Propagation Conference 2012 (LAPC 2012), Loughborough, UK, November 12-13, 2012.

N. H. Noordin, Ahmet T. Erdogan, Brian Flynn, Tughrul Arslan, *Compact Directional Patch Antenna with Slotted Ring for LTE Frequency Band*, Loughborough Antennas & Propagation Conference 2012 (LAPC 2012), Loughborough, UK, November 12-13, 2012.

N. H. Noordin, Yan Chiew Wong, Ahmet T. Erdogan, Brian Flynn, Tughrul Arslan, *Meandered Inverted-F Antenna for MIMO Mobile Devices*, Loughborough Antennas & Propagation Conference 2012 (LAPC 2012), Loughborough, UK, November 12-13, 2012.

Rahmat Sanudin, **N. H. Noordin**, Tughrul Arslan, *DOA Estimation Using Modified Covariance Matrix*, Loughborough Antennas & Propagation Conference 2012, Loughborough, UK, November 12-13, 2012.

2011

N. H. Noordin, Ahmed O. El-Rayis, Nakul Haridas, Ahmet T. Erdogan, Tughrul Arslan, *Triangular Lattices for Mutual Coupling Reduction in Patch Antenna Arrays*, Loughborough Antennas & Propagation Conference 2011 (LAPC 2011), Loughborough, UK, November 14-15, 2011, pp. 1-4.

N. H. Noordin, Virgilio Zuniga, Ahmed O. El-Rayis, Nakul Haridas, Ahmet T. Erdogan, Tughrul Arslan, *Uniform Circular Arrays for Phased Array Antenna*, Loughborough Antennas & Propagation Conference 2011 (LAPC 2011), Loughborough, UK, November 14-15, 2011, pp. 1-4.

Wei Zhou, **N. H. Noordin**, Nakul Haridas, Ahmed O. El-Rayis, Ahmet T. Erdogan, Tughrul Arslan, *A WiFi/4G Compact Feeding Network for an 8-Element Circular Antenna Array*, Loughborough Antennas & Propagation Conference 2011 (LAPC 2011), pp. 1-4, Loughborough, UK, November 14-15, 2011.

Rahmat Sanudin, **N. H. Noordin**, Ahmed O. El-Rayis, Nakul Haridas, Ahmet T. Erdogan and Tughrul Arslan, *Analysis of DOA Estimation for Directional and Isotropic Antenna Arrays*, Loughborough Antennas & Propagation Conference 2011 (LAPC 2011), pp. 1-4, Loughborough, UK, November 14-15, 2011.

Rahmat Sanudin, **N. H. Noordin**, Ahmed O. El-Rayis, Nakul Haridas, Ahmet T. Erdogan and Tughrul Arslan, *Capon-Like DOA Estimation Algorithm for Directional Antenna Arrays*, Loughborough Antennas & Propagation Conference 2011 (LAPC 2011), pp. 1-4, Loughborough, UK, November 14-15, 2011.

Haoyu Zhang, **N. H. Noordin**, Ahmet T. Erdogan, Tughrul Arslan, *Smart Antenna Array for Brain Cancer Detection*, Loughborough Antennas & Propagation Conference 2011 (LAPC 2011), pp. 1-4, Loughborough, UK, November 14-15, 2011.

Yan Chiew Wong, **N. H. Noordin**, Ahmed O. El-Rayis, Nakul Haridas, Ahmet T. Erdogan, Tughrul Arslan, *An Evaluation of 2-phase Charge Pump Topologies with Charge Transfer Switches for Green Mobile Technology*, 20th IEEE International Symposium on Industrial Electronics (ISIE 2011), pp. 136-140, Poland, Jun 27-30, 2011.

1.4 Thesis structure

In Chapter 2, a polarisation reconfigurable microstrip antenna is proposed. Microstrip antenna design techniques to achieve circular polarisation are discussed. The proposed antenna achieves different polarisation states, namely, linear polarisation (LP), left-hand circular polarization (LHCP) and right-hand circular polarisation (RHCP), by perturbing the shape of its main radiating structure. Key dimensions of the antenna are varied in order to understand their effect on the radiation properties of the antenna.

Chapter 3 explores the design of an array with wide scan coverage for use in wireless communication systems. Various configurations such as a uniform linear array, a uniform circular array and faceted arrays, are considered. The influence of different design parameters, such as number of elements, separation between elements and orientation of the elements, to the scanning range of the array is analysed. This chapter also presents the procedures of synthesising the 3-faceted array for low sidelobe level. Phase corrections together with amplitude tapering technique are used, which allows the faceted structure to be synthesised for low sidelobe level (SLL) in a similar way to the linear array. Amplitude tapering techniques discussed in this chapter include conventional windows, such as Binomial and Hamming Windows, and tuneable windows, such as Taylor and Kaiser Windows.

In Chapter 4, the performances of the faceted arrays, described in Chapter 3, are evaluated. The faceted arrays are compared in the context of adaptive beamforming properties. The beamforming is achieved with two different optimisation criteria, namely, minimum MSE and maximum SINR. This chapter also discusses beamforming algorithms for wireless communication systems. Beamforming algorithms using different optimisation criteria, namely, minimum Mean Square Error (MSE), blind beamforming, maximum signal-to-interference ratio (SINR) and power minimisation are explored. The adaptive algorithms and biologically inspired algorithms are used in order to achieve the criteria.

Chapter 5 discusses the beamforming implementation strategy is which are the single-port and multi-port beamforming architectures. A single-port beamforming technique using pseudo-inverse function is proposed and implemented in the beamforming algorithm that uses minimum MSE as the optimisation criteria. Radiation patterns generated by this technique are then compared with the multi-port beamforming system.

Chapter 6 summarises and concludes this thesis. In addition, the contribution of this thesis is re-highlighted and further research based on the techniques developed in this thesis is suggested.

1.5 Summary

Adaptive array antennas have the potential to be used in wireless communication devices. The technology could optimise the wireless channel usage while minimising the power consumption of the devices. However, due to high implementation cost and hardware complexity, adaptive array antennas are not used commercially. This thesis proposes an adaptive array antenna design for wireless communication devices, where particular attention is given to:

i. low-profile reconfigurable antenna design,

ii. wide scanning range array design, and

iii. single-port beamforming technique.

Chapter 2

Polarisation Reconfigurable Antenna Design

2.1 Introduction

This chapter discusses the design of a polarisation reconfigurable antenna for use in wireless communication systems. The radiation pattern of an adaptive array antenna is dependent on the individual radiation pattern of the array element and the geometry of the array. An array of directional antennas will generate a radiation pattern with narrow main beam. This kind of array is better suited to systems with limited power and those that involve data communication with known locations. Apart from that, low profile antennas, such as microstrip antennas, are more suitable than other types of antenna due to the limited space available on wireless communication devices. Therefore, besides having the ability to radiate different polarised waves, the antenna should be compact and have a directional radiation pattern. This chapter is divided into seven sections. The theory behind the antenna design is presented in Section 2.2 and Section 2.3 discusses the designs of existing polarised reconfigurable antenna. The proposed antenna structure is modelled in CST Design Suite 2011 and the analysis of varying key dimensions on the antenna performance is discussed in Section 2.4 and Section 2.5, respectively. The performance on the antenna is discussed in Section 2.6 and finally, Section 2.7 summaries the chapter.