Wideband Compact Antennas for MIMO Wireless Communications

Dinh Thanh Le

A dissertation submitted in partial fulfillment

of the requirements for the degree of

Doctor of Engineering

in

Electronic Engineering



The University of Electro-Communications March 2012

Copyrights

© Copyright by Dinh Thanh LE, 2012 All Rights Reserved Approved by Supervisory Committee:

Chairperson:	Profesor Yoshio KARASAWA
Members:	Profesor Takeshi HASHIMOTO
	Profesor Nobuo NAKAJIMA
	Assoc. Profesor Kouji WADA
	Assoc. Profesor Yoshiaki ANDO

Kính tặng Bà, Bố Mẹ, các Anh Chị và Mai Hoa yêu!

> Tokyo, tháng 3 năm 2012 Lê Đình Thành

Acknowledgements

A numbers of people have given their hands to support me throughout my work. A few words written here could not adequately capture all appreciation from the bottom of my heart.

First of all, I would like to express my sincere respect and deepest gratitude to my principal advisor and mentor, Professor Yoshio Karasawa. His continuous guidance and encouragement has been a critical factor for me to open the door into the real science garden of the world. My experience working under his supervision is among the best I have known. The knowledge, experience, and skills that I have gained during my doctoral course under Prof. Karasawa's guidance are invaluable in my professional work, and I am very much obliged to him for his aid during my academic adventure. It has been my greatest honor and privilege working under such a prominent scientist.

I would like to thank Prof. Takeshi Hashimoto, my secondary advisor, for his kind supervision and supports during my works. His comments on this manuscript make it concise and clearer.

I give my special thanks to Prof. Yoshiaki Ando for his precious comments and discussions throughout my studies. His kind review on journal papers I submitted in this course is invaluable. My gratitude and many thanks also go to Prof. Nobuo Nakajima and Prof. Akira Saito for their kind guidance and instruction in antenna manufacturing and measurements during my researches. I have learnt a lot from them. I would also like to thank supervisory committee members for reviewing my thesis. Their time, advice, and criticism are greatly appreciated.

I am grateful to Prof. Yutaka Ikeda, Prof. Mikio Shiga and all Japanese language teachers for building up my Japanese skills from a very beginner. Besides having a lot of joys in Japanese classes, I have also studied much about Japanese culture during my time in the country of cherry blossoms.

I gratefully acknowledge Ministry of Education and Training of Vietnam for offering me a full three-year scholarship to pursue a doctoral course in Japan. Without this financial support, it would be impossible for me to complete my doctoral education.

I especially want to acknowledge all members of Karasawa laboratory who have shared with me all the facilities with which I have carried out most of my work and research. They have provided me a pleasant and friendly working environment. My mind also goes to the rest of colleagues and friends at the University of Electro-communications as well as Hitotsubashi dormitory for the wonderful time we had together. Many thanks go to the staffs of my department and international student office for their kindness and their priceless help every time I asked for.

I am thankful for my wife, Mai Hoa, for her love and unyielding support for the last 6 years. She has been with me every step of the whole journey. Finally, I am forever indebted to my parents, my sisters and brothers, for their understanding, endless patience and encouragement.

Tokyo, 29th Jan. 2012 Dinh Thanh LE

Summary

Recent years, the demand of high data rates in wireless communication systems has rapidly increased. Among the promising candidates responding to the demand, multi-input multi-output (MIMO) systems have been received much research attention. Compared with the conventional singleinput single-output (SISO), a MIMO system can improve channel capacity without upgrading the transmitter's power supply and widening the bandwidth. In MIMO techniques, antenna issues such as operating bandwidth, element radiation patterns, array configuration, element polarization, mutual coupling, and array size may have strong effects on channel capacity. Therefore, these issues should be taken into account in new antenna designs for MIMO systems. Recently, many types of compact MIMO antennas have been introduced. However, there are still several drawbacks such as high mutual coupling, narrow bandwidth, and large size. This dissertation will make a contribution on new designs of MIMO antennas with main focus on wide operating bandwidth and compact size issues. Furthermore, experiments on MIMO schemes, which utilize proposed antennas, are also conducted with detailed discussions and results.

Firstly, two compact wideband MIMO antennas with tri-polarization are proposed. One has three ports formed in an "H" shape, and the other has six ports formed in a cube. Antenna elements are formed in compact sizes, yet mutual couplings between them are kept under -18 dB. These MIMO antennas can offer a relative bandwidth of over 16%. In addition, several

measurements of MIMO systems utilizing the proposed antennas in two typical environments, line-of-sight (LOS) and non-line-of-sight (NLOS) propagations, have been carried. The results of these measurements show wideband MIMO characteristics of the antennas.

Secondly, we propose a simple broadband antenna that is suitable for broadband wireless applications. The antenna can offer a bandwidth of over 50%. In addition, two MIMO antennas, of which elements are similar to the broadband antenna, are proposed. One consists of two ports, and the other consists of four ports. Measurement results show that mutual coupling between ports in these MIMO antennas are kept under -10 dB at low frequency region, and -20 dB at high frequency region of the bandwidth of the MIMO antennas. Furthermore, we utilized the broadband MIMO antennas in some MIMO experiments to examine channel capacity in a wide frequency range. Measurement results indicate the change of channel capacity over a wide frequency range.

Finally, basing on the 50%-bandwidth antenna above, we introduce a novel ultra-wideband (UWB) antenna. This antenna offers a relative bandwidth of 95.5%, covering a frequency range of 3.5-9.9 GHz, making it suitable for UWB communications. Furthermore, since its design is simple and compact, we may utilize the antenna to form UWB-MIMO antennas.

MIMO無線通信のための広帯域コンパクトアンテナに関する研究

レ・ディン・タン

Le Dinh Thanh

論文概要

近年、無線通信システムにおける高データレートの需要が急速に増加してい る。その中に、MIMO(多入力多出力システム)に関する研究が注目されてい る。MIMOシステムは、送信側と受信側で複数のアンテナを利用することで、 送信電力を増加せず、または使用する帯域幅を広げないまま、システムの通 信路容量を向上させることができる。MIMOシステムでは、動作帯域幅、素子 の放射パターン、アレイ構成、偏波、アンテナ素子間相互結合、および配列 のサイズなどのアンテナの問題を考慮した設計が必要になる。既存のMIMOア ンテナの大部分は、動作帯域幅が狭く、寸法が大きい。本論文では、広帯域 かつコンパクトであることの要求を考慮したMIMOアンテナ設計について示す。 また、アンテナの設計とMIMO実験に関する詳細な検討結果について述べる。

最初に、直交三偏波を持つ二つの小型広帯域MIMOアンテナの設計法を述べる。 一方は、"H"状に形成された3つのポートを有するアンテナである。他方は、 キューブ状で形成された6つのポートを持つものである。デザインはコンパク トであるが、ポート間で低い相互結合特性を持つ。さらに、2つの典型的な伝 搬環境において、提案アンテナを利用したMIMO実験:見通し内(LOS)と見通 し外(NLOS)の伝送特性測定実験を行った。又、測定データを用いて3直交偏 波利用広帯域MIMOの通信路容量の評価を行った。

次に、MIMOコグニティブ無線のための簡易かつコンパクトな広帯域アンテナ の設計を行った。このアンテナをアレイ化した2種類のMIMO広帯域アンテナ の伝送特性を評価した。一方は、2ポートのアレイアンテナであり、他方は4 ポートのアレイアンテナである。さらに、これらの広帯域アレイアンテナを 用いた実験によって広帯域でのMIMOの特性を調べた。その結果、広帯域にお ける良好なMIMO通信路容量特性を実現することができ、超広帯域特性が 要求されるコグニティブ無線での利用に有効であることが分かった。 最後に、上記で提案した広帯域アンテナをさらに広帯域化して、超広帯域 (UWB)ダイポールアンテナとしての設計を行った。このアンテナの特性シミ ュレーション解析と、電波暗室内での特性測定実験も行った。その結果、提 案したUWBアンテナは周波数3.5GHz-9.9GHzで良好な特性を有することが確認 でき、今後のUWB - MIMO通信システム用のアンテナとして、有望であること が分かった。

Contents

Co	ontent	ts		X
Li	st of I	igures		xiii
Li	st of]	[ables		xvii
1	Intr	oductio	n	1
	1.1	Contex	at of Work	1
	1.2	Main (Contributions	3
	1.3	Outlin	e of Thesis	3
2	Bacl	kground	ds and Literature Review	6
	2.1	Basic	Concepts	6
		2.1.1	Antenna	6
		2.1.2	MIMO Antenna	8
	2.2	MIMC	Backgrounds	9
		2.2.1	Benefits of MIMO	9
		2.2.2	MIMO Channel Modeling	10
		2.2.3	Channel Capacity of MIMO Systems	15
	2.3	Anteni	nas for MIMO Systems	16
		2.3.1	Element Radiation Pattern	17

CONTENTS

		2.3.2	Array Configuration	17
		2.3.3	Mutual Coupling Reduction	20
		2.3.4	MIMO Antennas in Advanced Systems	21
	2.4	Chapte	er Summary	21
3	Wid	eband (Compact MIMO Antennas with Tri-Polarization	23
	3.1	Antenn	na Element	23
	3.2	Three-	port Orthogonal Polarization Antenna	25
		3.2.1	Antenna Configuration	25
		3.2.2	Main Characteristics	25
	3.3	Cube-s	six-port Antenna	28
		3.3.1	Antenna Design	30
		3.3.2	Main Characteristics	30
	3.4	Wideb	and MIMO Experiments	33
		3.4.1	Experiment Environments	36
		3.4.2	Channel Characteristics	40
		3.4.3	Channel Capacity	44
	3.5	Chapte	er Summary	51
4	Broa	adband	Antennas for MIMO Cognitive Radio	53
	4.1	Broad	band Antenna Design	53
		4.1.1	Antenna Configuration	54
		4.1.2	Operation Principle	55
		4.1.3	Key Parameter Studies	56
		4.1.4	Current Distribution	58
		4.1.5	Measurement Results	58
	4.2	Broadl	band MIMO Antennas	61
		4.2.1	Two-Port MIMO Antenna	62

CONTENTS

		4.2.2	Four-Port MIMO Antenna	64
	4.3	Broadb	and MIMO Experiments	66
		4.3.1	Environment and Experiment Setup	67
		4.3.2	Correlation Parameter	70
		4.3.3	Channel Capacity Estimation	73
	4.4	Chapte	r Summary	75
5	A Co	ompact	UWB Antenna	77
	5.1	Introdu	action of UWB antennas	77
	5.2	Compa	ct UWB Dipole Antenna	78
		5.2.1	Antenna Design	78
		5.2.2	Results and Discussion	79
		5.2.3	Key Parameter Studies	82
	5.3	Chapte	r Summary	85
6	Con	clusions	and Future Work	87
	6.1	Conclu	sions	87
	6.2	Future	Work	89
Ap	Appendix A 90			
Re	feren	ces		94
Pa	pers 1	related t	to the thesis	104
Pu	blisho	cations		105
Au	thor bibliography 108			

List of Figures

2.1	MIMO configuration	11
2.2	Channel matrix	11
2.3	Equivalent channel	12
2.4	Distribution functions of $N_t \times N_r$ MIMO: solid lines are obtained by	
	theoretical calculation and dashed lines are by Monte Carlo simula-	
	tions. (a) 3×3 MIMO; (b) 3×6 MIMO	14
2.5	Water filling method	16
2.6	MIMO cube	18
2.7	The MIMO antenna configuration in [5]: (a) antenna elements, (b) the	
	3D view	19
3.1	Configuration of the antenna element	24
3.2	Cutaway balun in [47]	24
3.3	Three-port orthogonal polarization antenna: (a) dipole 1, 2; (b) dipole	
	3; (c) the 3-D view; (d) the practical antenna.	26
3.4	The VSWR characteristics of the three-port antenna	27
3.5	The inter-port isolation of the three-port antenna	28

3.6	Measured cross-polarization (dashed line) and co-polarization (solid	
	line) radiation patterns of the three-port antenna: (a) Port 1 E-plane;	
	(b) Port 1 H-plane; (c) Port 2 E-plane; (d) Port 2 H-plane; (e) Port 3	
	E-plane; (f) Port 3 H-plane	29
3.7	The cube-six-port antenna: (a) dipoles 1, 2 and 3; (b) dipoles 4, 5 and	
	6; (c) the 3-D view; (d) the practical cube	31
3.8	The VSWR characteristics of the cube	32
3.9	The inter-port isolations of the cube-six-port MIMO antenna	33
3.10	Measured cross-polarization (dashed line) and co-polarization (solid	
	line) radiation patterns of the cube-six-port antenna: (a) Port 1 E-plane;	
	(b) Port 1 H-plane; (c) Port 2 E-plane; (d) Port 2 H-plane; (e) Port 3	
	E-plane; (f) Port 3 H-plane	34
3.11	Measured cross-polarization (dashed line) and co-polarization (solid	
	line) radiation patterns of the cube-six-port antenna: (a) Port 4 E-plane;	
	(b) Port 4 H-plane; (c) Port 5 E-plane; (d) Port 5 H-plane; (e) Port 6	
	E-plane; (f) Port 6 H-plane	35
3.12	The reverberation chamber	37
3.13	Measurement setup	38
3.14	Indoor experiment room: (a) a photograph of indoor experiments viewed	
	from Rx point to Tx point; (b) the layout of the room	39
3.15	Typical received signals	42
3.16	PDFs for the magnitude of normalized received signals	43
3.17	CDFs of normalized eigenvalues for MIMO systems with the "Com3	
	\times Com3" configuration in difference environments: (a) reverberation	
	chamber; (b) Indoor.	45

LIST OF FIGURES

3.18	CDFs of normalized eigenvalues for MIMO systems with the "Com3	
	\times Com6" configuration in different environments: (a) reverberation	
	chamber; (b) Indoor.	46
3.19	CDFs of normalized eigenvalues for MIMO systems with the "Com6	
	\times Com6" configuration in different environments: (a) reverberation	
	chamber; (b) Indoor.	47
3.20	Averaged channel capacity for different polarization diversities: (a) In	
	reverberation chamber; (b) In Indoor	49
3.21	Averaged channel capacity for different antenna number: (a) In rever-	
	beration chamber; (b) In Indoor.	50
41	Configuration of the antenna: (a) layout geometry (b) front view of	
7,1	the prototype (c) back view of the prototype	54
12	Width of substrate $(1 - 20.5 \text{ mm}, d - 28 \text{ mm})$	55
4.2	Vidu of substate $(t = 20.5 \text{ mm}, u = 26 \text{ mm})$	55
4.5	Length of dipole and $(y = 15 \text{ mm}, a = 28 \text{ mm})$	56
4.4	which of grounding part $(y = 15 \text{ mm}, t = 20.5 \text{ mm})$	30
4.5	Simulated vector surface current distribution on the proposed dipole:	
	(a) 2.3 GHz; (b) 3.2 GHz; (c) 3.9 GHz	58
4.6	Antenna VSWR characteristic	59
4.7	Measured antenna peak gain in XY plane	59
4.8	Measured cross-polarization (dashed line) and co-polarization (solid	
	line) radiation patterns of the antenna: (a) E-plane 2.4 GHz; (b) H-	
	plane 2.4 GHz; (c) E-plane 3.2 GHz; (d) H-plane 3.2 GHz; (e) E-plane	
	4.0 GHz; (f) H-plane 4.0 GHz	60
4.9	The configuration of two-port MIMO antenna	62
4.10	VSWR characteristics of the two-port MIMO antenna	63
4.11	Inter-port isolation of the two-port MIMO antenna	64
4.12	The configuration of the four-port MIMO antenna	65

LIST OF FIGURES

4.13	VSWR characteristics of the four-port MIMO antenna	66
4.14	Inter-port isolation of the four-port MIMO antenna	66
4.15	Experiment chamber	67
4.16	PDFs for the magnitude of normalized received signals in different	
	sub-bands	69
4.17	Correlation coefficient of sub-channels	72
4.18	Channel capacity (SNR = 10 dB)	73
F 1		70
5.1	Geometry of proposed antenna	78
5.2	Photograph of the fabricated antenna.	78
5.3	Measured and simulated VSWR of the proposed antenna	80
5.4	Measured cross-polarization (dashed line) and co-polarization (solid	
	line) radiation patterns of the antenna:: (a) E-plane 3.5 GHz; (b) E-	
	plane 5.5 GHz; (c) E-plane 7.5 GHz; (d) E-plane 9.7 GHz; (e) H-plane	
	3.5 GHz; (f) H-plane 5.5 GHz; (g) H-plane 7.5 GHz; (h) H-plane 9.7	
	GHz	81
5.5	Measured antenna gain [dBi] in XY plane	81
5.6	Simulated current distributions	83
5.7	Effects of varying width of substrate	84
5.8	Effects of varying length of dipole	84
5.9	Effects of varying length of loaded patch	85

List of Tables

3.1	A comparison between the three-port antenna and the antenna in $[5]$.	27
3.2	Antenna configuration in MIMO experiments	37
3.3	Normalization factors (N_F)	41
4.1	The optimum geometrical parameters (mm)	57
5.1	The optimum geometrical parameters (mm)	79

Chapter 1

Introduction

1.1 Context of Work

In recent years, many advanced techniques have been developed to improve data rates in wireless communications. Among these techniques, the Multi-Input Multi-Output (MIMO) transmission scheme is one of the most promising methods. In MIMO systems, antenna issues such as operating bandwidth, element radiation patterns, array configuration, element polarization, mutual coupling, and array size have critical impacts on channel capacity [1], [2]. Thus, topics related to antennas for MIMO systems has been a main focus in many research groups.

An antenna array for MIMO systems, also referred to as MIMO antennas, consists of a number of antenna elements in a particular configuration. In order to enhance channel capacity, mutual couplings between elements should be kept under a low value. Furthermore, the configuration of the MIMO antenna should be compact to save space in a real application. However, if elements of the MIMO antenna are configured too close to each others (for a compact design), mutual couplings between them will increase, thus channel capacity will be reduced significantly. Moreover, for wideband MIMO communications, the MIMO antenna should also work in a wide frequency range. Therefore, design of wideband compact MIMO antennas is an interesting topic in antenna research. Currently, several designs of compact MIMO antennas have been introduced [3]-[9]. These antennas are formed in compact size, but mutual couplings between elements are still high. Nevertheless, they only offer a narrow operating bandwidth. For example, relative bandwidth is only 2% in [4], 5% in [5], or so on. In this work, we will propose new wideband compact MIMO antennas. Some of these MIMO antennas can offer a bandwidth of over 50%, making them applicable for wideband MIMO communications, including MIMO in cognitive radio.

Furthermore, while narrowband MIMO experiments have been presented recently in [10]- [13], there are few papers reporting MIMO performances for a wide bandwidth. Therefore, measuring channel capacity of MIMO systems with different wideband MIMO antennas in different environments, including reverberation chamber, indoor or outdoor, would be also an interesting point. We will make a contribution in this open field by conducting some MIMO measurements with our MIMO antennas.

Finally, working further toward the design of wideband antennas, we found that not many compact antennas for UWB-MIMO communications have been introduced up to present. Most of single UWB antennas have complex design and large size. Thus, they would not be suitable in forming UWB-MIMO antennas. Therefore, we will propose a simple, compact UWB antenna for UWB communications. Thanks to its compact size, the proposed UWB antenna is very promising as the base to develop a UWB-MIMO antenna in future research. Main contributions of our work are presented in the following section.

1.2 Main Contributions

This thesis contributes in the designs of wideband compact MIMO antennas and measurement techniques for computing channel capacity of MIMO systems over a wide frequency range.

Firstly, we propose two wideband compact MIMO antennas: one consists of three ports, and the other consists of six ports. We utilize these MIMO antennas in several measurements in two typical environments: line-of-sight (LOS) and non-line-of-sight (NLOS) propagations to characterize performance of wideband MIMO systems. The results of these experiments show averaged channel capacity of wideband MIMO systems with tri-polarizations.

Secondly, a simple broadband antenna is proposed for advanced wireless communications such as cognitive radio applications. Based on the proposed broadband antenna, two broadband MIMO antennas, one has two ports and the other has four ports, are developed. These MIMO antennas are simple, compact, yet offer a wide operating frequency range with low mutual coupling. The broadband MIMO antennas are utilized in MIMO measurements to explore the change of channel capacity over a wide frequency range for cognitive radio applications.

Finally, we introduce a novel compact UWB dipole antenna that aims at the use for UWB-MIMO antennas. The UWB antenna is developed from the proposed broadband antenna with some modifications and optimization. Measurement results are shown and some discussions on antenna performance are presented.

1.3 Outline of Thesis

The thesis consists of six chapters, of which the author's main contributions are presented in chapters 3, 4, and 5.

Chapter 2: In this chapter, the background of MIMO techniques and an overview

of MIMO antenna issues will be presented. The summary of MIMO includes brief introduction of the improvements of using MIMO compared with SISO systems, MIMO channel model, and channel capacity of MIMO systems in eigen mode. Additionally, the chapter gives an overview of MIMO antenna and its aspects which affect on MIMO performance. Challenging in MIMO antenna designs are also discussed with some current research trends.

Chapter 3: We firstly proposed two compact wideband MIMO antennas, one has three ports and the other has six ports, in this chapter. These MIMO antennas are designed from a new printed dipole element which consists of a dipole and a symmetric balun strip. For these MIMO antennas, relative bandwidth is over 16% for VSWR less than 2; mutual coupling is under -18 dB and -20 dB for the three-port antenna and the six-port antenna respectively. Secondly, we utilized the compact MIMO antennas for some MIMO experiments to examine how the antennas work in practical systems. Measurement results of channel capacity of wideband MIMO systems with tri-polarizations are presented.

Chapter 4: In the first part of this chapter, we focus on a design of a simple compact broadband antenna. Antenna operating principle, as well as main characteristics are presented. Next, using the proposed broadband antenna as elements, we introduce two simple broadband MIMO antennas. Both these MIMO antennas keep low mutual couplings in compact sizes. Furthermore, we utilize the broadband MIMO antennas in several measurements, in which MIMO systems are assumed to be operated in cognitive radio in a wide frequency range. The results of these measurements show how channel capacity of a MIMO system change in a wide frequency region.

Chapter 5: This chapter indexes our novel design of a compact UWB dipole antenna. It is developed from the broadband antenna in chapter 4 with some additional components. The size of this UWB antenna is only 57 mm \times 9 mm \times 1.6 mm. In fact, its length is slightly long compared with some available UWB antennas. However, its

width (only 9 mm) is one of the smallest among existing UWB antennas. The proposed UWB antenna can be easily utilized to form UWB-MIMO antennas in further research.

Chapter 6: Chapter 6 presents concluding remarks of this thesis and some future works.

Chapter 2

Backgrounds and Literature Review

2.1 Basic Concepts

2.1.1 Antenna

Antenna

According to the IEEE standards definitions of terms for antenna (IEEE Std 145-1983), the antenna is defined as a "part of a transmitting or receiving system which is designed to radiate or to receive electromagnetic waves" [14]. It is the transitional structure between free-space and a guiding device [15]. Although there are a number of parameters characterizing an antenna, but to describe its performance, only some main parameters are considered such as radiation pattern, gain, bandwidth, voltage standing wave ratio/ return loss, or so on.

Radiation pattern

Radiation pattern of an antenna is defined as "a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is determined in the far-field region and is represented as a function of the directional coordinates" [14], [15]. In our work, when

proposing a new antenna, we also measure radiation pattern to specify its performance. Antenna radiation pattern is measured inside an anechoic chamber.

Voltage standing wave ratio/ Return loss

Return loss (RL) is a measure of the effectiveness of power delivery from a transmission line to a load such as an antenna. If the power incident on the antenna-under-test is P_{in} and the power reflected back to the source is P_{ref} , the degree of mismatch between the incident and reflected power in the traveling waves is given by the ratio P_{in}/P_{ref} . Expressed in dB, it is written as

$$RL = 10\log_{10}\left(\frac{P_{in}}{P_{ref}}\right)(dB).$$
(2.1)

In terms of the reflection coefficient ρ , return loss can be expressed as

$$RL = -20\log_{10}|\rho| \, (dB). \tag{2.2}$$

In terms of the voltage-standing-wave-ratio (VSWR), return loss can be expressed as

$$RL = 20\log_{10} \left| \frac{VSWR + 1}{VSWR - 1} \right|.$$
(2.3)

In many papers related to design of antennas, return loss or VSWR is normally used to describe antenna performance. In our work, we use the VSWR characteristic to specify antenna bandwidth.

Bandwidth

The bandwidth of an antenna is referred to as "the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard"[15]. Therefore, if antenna characteristics are within an acceptable value in a frequency range, then the range is considered to be the antenna bandwidth. This frequency range is also referred to as the "absolute bandwidth" of an antenna.

In most of papers in *IEEE Transactions on Antennas and Propagation*, antenna bandwidth is considered as a frequency range where reflection coefficient is less than -10 dB, or in some others, VSWR is less than 2. Depending on applications, there are also papers that considered antenna bandwidth to be a frequency range where VSWR is less than 3. In this thesis, the frequency range, where VSWR less than 2, is considered as antenna bandwidth.

In order to compare the bandwidth of different antennas, a relative bandwidth is also widely used. It is the ratio of absolute bandwidth and the center frequency of the bandwidth. Let f_1 and f_2 are the lowest frequency and the highest frequency of the bandwidth of an antenna, the relative bandwidth of the antenna is calculated as

$$BW = \frac{200(f_2 - f_1)}{f_2 + f_1}\%.$$
(2.4)

According to the Federal Communications Commission (FCC), Ultra-Wideband (UWB) may be used to refer to any radio technology having bandwidth exceeding of 500 MHz or 20% of relative bandwidth [16].

Balun

The word "Balun" comes from **Bal**ance-**Un**balance description in antenna. In antenna, a balun is used as an electrical transformer that converts electrical signals from unbalanced source (for example from a coaxial) to a balanced antenna (for example a dipole). Within a good balun, currents on antenna following back to connectors will be reduced significantly. Therefore, antenna may also achieve a larger bandwidth.

2.1.2 MIMO Antenna

An antenna array for MIMO systems is referred to as a *MIMO antenna*. If the configuration of the MIMO antenna is compact, it is called as *a compact MIMO antenna*. Furthermore, the number of ports in a MIMO antenna corresponds to the number of elements of it. Therefore, sometimes, it is known as *an N-port MIMO antenna*, where *N* is the number of port.

2.2 MIMO Backgrounds

2.2.1 Benefits of MIMO

Over the past decade, wireless communication systems using multiple antennas at both transmitter and receiver, Multi-Input Multi-Output (MIMO) systems, have been developed. Compared with the conventional SISO (Single-Input Single-Output) systems, MIMO systems can offer much greater performances. The improvement in MIMO systems comes from array gain, diversity gain, spatial multiplex gain, and interference reduction [17]. They are explained briefly in the following.

Array gain: Since multiple antennas are used at transmitter and receiver, signal to noise ratio (SNR) will be increased thanks to the coherent combining effect of signals at the receiver. Array gain in MIMO is the increase of SNR. Array gain depends on the number of antennas used in the system and on the channel knowledge in transmitter and receiver.

Diversity gain: Diversity gain is the gain achieved from mitigating fading of wireless channel by the diversity techniques. These techniques rely on transmitting multiple copies of the signal over independently fading paths. By doing so, it is expected that at least one of the copy will avoid a deep fade during propagation. Thus, quality and reliability of reception will be improved.

Spatial multiplex gain: This gain is realized by transmitting independent data streams via multiple antennas. Under good channel conditions, for example in multipathrich environment, the receiver can separate the different streams, thus improving channel capacity.

Interference reduction: Since multiple antennas are utilized, we can adaptively control signal energy towards the determined users and reduce signals from directional interferers by changing radiation patterns of the array.

In fact, realization of the mentioned benefits can not be possible at a same time or even at a defined system because it depends on transceiver design. For example, channel capacity of a MIMO system can be much improved if the number of antennas is large, but system drawbacks such as complexity, cost, or size will be also considerably raised. Even so, in comparison with the conventional SISO systems, these benefits promote MIMO techniques to be one of the key schemes for gigabit wireless communications.

2.2.2 MIMO Channel Modeling

A basic MIMO model is illustrated in Fig. 2.1 in which the propagation environment consist of a number of scatterers, reflectors, or/and diffrators. Depending on the strength of the direct signal traveling from transmitters to receivers, propagation environment are divided into two types: the line-of-sight (LOS) and the none-line-of-sight (NLOS) environment. In the LOS environment, typically found in outdoor, a direct signal from the transmitter to the receiver is relatively strong compared with the total of reflected signals. On the other hands, the direct signal is weak or do not exist in the NLOS environment, found in a reverberation chamber.

For a MIMO channel which has N_t transmit antennas and N_r receive antennas, the channel matrix $\mathbf{A}(f)$ in frequency domain can be written as

$$\mathbf{A}(f) = \begin{bmatrix} a_{11}(f) & \cdots & a_{1N_t}(f) \\ \vdots & \ddots & \vdots \\ a_{N_t}(f) & \cdots & a_{N_t}(f) \end{bmatrix}$$
(2.5)

where $a_{rt}(f)$ represents the gain between the t^{th} transmitter and r^{th} receiver antennas



Figure 2.1: MIMO configuration



Figure 2.2: Channel matrix

 $(1 \le r \le N_r \text{ and } 1 \le t \le N_t)$. Using singular-value decomposition (SVD), we can express the matrix **A** as

$$\mathbf{A} = \mathbf{E}_r \mathbf{D} \mathbf{E}_t^{\mathbf{H}} = \sum_{i=1}^{N_0} \sqrt{\lambda_i} \cdot \mathbf{e}_{r,i} \cdot \mathbf{e}_{t,i}^{\mathbf{H}}$$
(2.6)

where

$$\mathbf{D} \equiv \operatorname{diag}\left[\sqrt{\lambda_1} \sqrt{\lambda_2} \cdots \sqrt{\lambda_{N_0}}\right] \tag{2.7}$$



Figure 2.3: Equivalent channel

$$\mathbf{E}_{t} \equiv \begin{bmatrix} \mathbf{e}_{t,1} \ \mathbf{e}_{t,2} \cdots \mathbf{e}_{t,N_0} \end{bmatrix}$$
(2.8)

$$\mathbf{E}_{r} \equiv \begin{bmatrix} \mathbf{e}_{r,1} \ \mathbf{e}_{r,2} \cdots \mathbf{e}_{r,N_0} \end{bmatrix}$$
(2.9)

$$N_0 \equiv \min(N_t, N_r). \tag{2.10}$$

The singular values λ_i ($i = 1, 2, ..., N_0$), arranged in descending order of value, are the eigenvalues of the correlation matrix $\mathbf{AA^H}$ where (.)^H is Hermitian operator. The vectors $\mathbf{e}_{t,i}$ and $\mathbf{e}_{r,i}$ respectively are the eigenvectors associated with eigenvalues λ_i of matrix $\mathbf{A^HA}$ and $\mathbf{AA^H}$.

By expanding the channel matrix in this approach, we can represent the propagation paths for a MIMO channel in a simpler way as illustrated in Figs. 2.2 and 2.3. Fig. 2.2 presents the channel matrix representing Eq. (2.5), whereas Fig. 2.3 shows the equivalent circuit representing in SVD. As can be seen in Fig. 2.3, the MIMO channel offers N_0 independent transmission paths. In this representation, the spatial multiplex gain is highlighted visually by the number of singular values, λ_i . As shown in Eq. (2.7) and Fig. 2.3, the gain amplitude of each path, depending on respective eigenvalues, is equal to $\sqrt{\lambda_i}$ where $\sqrt{\lambda_1}$ is the greatest and $\sqrt{\lambda_{N_0}}$ is the smallest value. These virtual paths are called as eigenpaths. The first eigen-path, respective to $\sqrt{\lambda_1}$, is referred to as the primary, while the second or lower eigenvalue paths are minor.

The statistical characteristics of the MIMO channel have been an interesting research topic so far. For the largest eigenvalue, a closed form expression has been investigated [18]. On the other hands, the expression of smallest eigenvalue is examined in [19]. In addition, in [20], the authors presented a method to calculate theoretical expressions for the marginal distribution of all eigenvalues of MIMO correlation matrices in the i.i.d. Rayleigh fading environment. The method is based on the calculations for the largest eivenvalue. The marginal distribution functions of ordered eigenvalues are expressed by liner combination of polynomials each multiplied by an exponential. Following this method, we have calculated the marginal probability density functions (PDF) of eigenvalues of some MIMO configurations which are investigated in this thesis. For instance, the density functions $p(\lambda)$ of the eigenvalues of the $3 \times N_r$ MIMO in the i.i.d. Rayleigh fading channel are calculated as

$$p(\lambda_1) = a_0(\lambda_1) e^{-\lambda_1} - a_1(\lambda_1) e^{-2\lambda_1} + a_2(\lambda_1) e^{-3\lambda_1}$$
(2.11)

$$p(\lambda_2) = a_1(\lambda_2) e^{-2\lambda_2} - 2a_2(\lambda_2) e^{-3\lambda_2}$$
(2.12)

$$p(\lambda_3) = a_2(\lambda_3) e^{-3\lambda_3}$$
(2.13)

where $a_i(\lambda)$ (*i* = 1, 2, 3) are polynomials. For $N_r = 3$, the polynomials can be expressed as

$$a_0(\lambda) = 3 - 6\lambda + 6\lambda^2 - 2\lambda^3 + \frac{1}{4}\lambda^4$$
(2.14)



Figure 2.4: Distribution functions of $N_t \times N_r$ MIMO: solid lines are obtained by theoretical calculation and dashed lines are by Monte Carlo simulations. (a) 3×3 MIMO; (b) 3×6 MIMO.

$$a_1(\lambda) = 6 - 6\lambda + 3\lambda^2 + \lambda^3 + \frac{1}{2}\lambda^4$$
(2.15)

$$a_2(\lambda) = 3. \tag{2.16}$$

From the density functions, we can easily calculate cumulative distribution functions (CDF) by taking integration of the probability density functions. For convenience, we calculated polynomials for a number of N_t and N_r and will present them in the appendix A. The theoretical calculations here will be used to compare with measured results presented in the next chapters.

We make a comparison between theoretical calculation and Monte Carlo simulation to verify the correctness of presented expressions. Fig. 2.4 illustrates the CDFs of eigenvalues of some MIMO schemes which are plotted by both calculations (solid line) and Monte Carlo simulations (histograms) using 10⁶ samples. As can be seen from these figures, calculation and simulation are in very good agreement.

2.2.3 Channel Capacity of MIMO Systems

The Shannon channel capacity of the additive white Gaussian noise SISO channel is calculated as

$$C = \log_2(1 + \gamma_0) \qquad \text{[bits/s/Hz]} \qquad (2.17)$$

where γ_0 is the receiver SNR. For the MIMO channel, there are two cases, depending on whether the transmitter knows or does not know the channel state information (CSI), channel capacity can be calculated differently. The first case is when only receiver has CSI, whereas the second case is when CSI is shared in both transmitter and receiver.

In the first case, when transmitter does not have CSI, transmitted power is divided equally to all transmitting antennas. This strategy is to try to avoid the worst scenario that we allocated large power to an antenna directing to null points of receivers. Then, channel capacity is calculated as

$$C = \sum_{i=1}^{N_0} \log_2 \left(1 + \frac{\lambda_i \gamma_0}{N_0} \right)$$
(2.18)

where γ_0 represents the SNR when all transmitted power is radiated from a single antenna and the same power is received on a single receive antenna. This means SNR is determined when we assume all power is transmitted via a virtual path having path gain of 1.

In the second case, the transmitted power will be optimally allocated to each transmitting antenna, according to the Water Filling (WF) rule [1], [21], [22]. An image of water filling rule is illustrated in Fig. 2.5. As can be seen from this figure, more power will be issued to paths which have greater eigenvalues (i.e., better gains). The formula



Figure 2.5: Water filling method

of channel capacity in this case can be expressed as

$$C_{WF} = \sum_{i=1}^{k_0} \log_2 \left(1 + \gamma_i \lambda_i\right)$$
(2.19)

where

$$\gamma_i = Q_{ik} = \frac{1}{k} \left(\frac{P_T}{\sigma^2} + \sum_{j=1}^k \frac{1}{\lambda_j} \right) - \frac{1}{\lambda_i}.$$
(2.20)

In (2.20), the value Q_{ik} must be repetitively computed for k = 1 to min (N_t, N_r) . The value k_0 used to compute in (2.19) will be chosen as the largest value of k such that with all values of i, the values Q_{ik_0} must be greater than 0. Also, in the expression of (2.20), the value P_T/σ^2 represents average SNR of a SISO system.

2.3 Antennas for MIMO Systems

In this section, we present an overview of the issues of MIMO antennas, including element radiation pattern, array configuration, and mutual coupling reduction techniques. Moreover, broadband and reconfigurable antennas, which are applicable in advanced wireless communication systems such as MIMO cognitive radio or UWB-MIMO, are also under consideration.

2.3.1 Element Radiation Pattern

In multipath environments, especially in multipath-rich environments, angle diversity can be exploited in propagation. For this purpose, a MIMO antenna, normally, consists of omnidirectional and/or directive antenna elements. For example, dipoles, which are a typical of omnidirectional antennas, are frequently used in MIMO antenna designs. Some researches have been conducted to investigate the effect of element radiation pattern on channel capacity of MIMO systems [23],[24]. It has been reported that more directive antenna elements can improve remarkably averaged channel capacity. However, in this case, the variation of channel capacity is a problem.

In another research, comparison in terms of channel capacity of systems which utilized dipole and spiral antennas (higher gain and more directive) has been carried in [24]. The spiral antenna mainly radiate toward $\pm 45^{0}$ from the azimuth plane, whereas the dipole has uniform radiation pattern in the same plane. As a result, it is highlighted that the system that utilized dipoles (lower gain) offers slightly better channel capacity. This is because these antennas radiate more energy into the azimuth plane where most of multipath components concentrated despite of propagation paths outside.

2.3.2 Array Configuration

The array configuration of a MIMO antenna, which affects directly the channel matrix **A** in Eq. (2.5), is also an important consideration. It would be difficult to answer which type of MIMO antenna configurations is the best in terms of maximizing channel capacity. Furthermore, if polarization is utilized, the combinations of antenna elements into a MIMO antenna recently create a number of different array configurations.

A remarkable research on array configuration is the MIMO cube in [3]. The cube consists of electrical dipole antennas in all the 12 edges as illustrated in Fig. 2.6. Both space and polarization diversities have been used to form the MIMO cube. Calculation results show that a huge theoretical capacity might be achieved in a system using MIMO cubes at the transmitter and receiver. For example, when the antenna element is a half-wavelength dipole, nine of the eigenpaths have a averaged gain greater than 0 dB, compared with gain of (1,1) antenna (the conventional SISO system). The highest averaged gain is about 17 dB. Furthermore, the calculated theoretical capacity is about 62.5 bps/Hz for a SNR of 20 dB. However, the cube is only suggested in theory. There is no practical cube mentioned in this paper. Moreover, the capacity was calculated without considering the practical issues such as mutual coupling, the matching of the dipoles, or the difficulty of forming the cube.

A number of other researches, which try to pack many antenna elements into a compact volume, have been reported with variation of array configurations [3]-[9]. Many of them exploit multiple orthogonal polarizations to reduce mutual coupling between antenna elements [3]-[7]. Most of these researches have been conducted with three ports in MIMO antennas with different antenna elements, including dipole, patch



Figure 2.6: MIMO cube
microstrip, or monopole. For example, the research in [5] suggested a simple MIMO antenna configuration with three elements as shown in Fig. 2.7. The elements are formed in two 51 mm \times 51 mm \times 1.6 mm FR4 epoxy boards. The center frequency is 2.5 GHz and mutual couplings are kept under - 18 dB. However, the antenna relative bandwidth is only 5%.

Moreover, a recent work [25] has reported two compact MIMO antennas. One consists of 24 ports and the other consists of 36 ports. The MIMO antennas are constituted by packing slot antenna and printed dipole antenna elements onto a cube. These MIMO antennas are not electrically small, but they can form a large number of elements in cubes. The 24-port MIMO antenna accounts a volume of $0.72\lambda_0^3$, whereas the 36-port MIMO antenna is packed in a cube of $1.13\lambda_0^3$. Here, λ_0 is the free space wavelength related to the center frequency of MIMO antenna bandwidth. In these MIMO antennas, polarization and spatial diversities have been utilized. Measurement results for the 36-port cube in a multipath-rich environment show that channel capacity up to 159 bps/Hz can be achieved for SNR of 20 dB.

Since the most of the mentioned MIMO antennas, which utilize only polarization diversity, can offer maximally three uncorrelated signals, the research in [26] has sug-



Figure 2.7: The MIMO antenna configuration in [5]: (a) antenna elements, (b) the 3D view.

gested that there are six distinguishable electric and magnetic states of polarization at a given point. Therefore, in multipath environments, it is possible to provide six uncorrelated signals at the receiver. Moreover, analysis of electromagnetic field polarizations have been presented in [27]. It is understood that when combining polarization and angle diversity, we can achieve six uncorrelated signals from three orthogonal polarization electric dipoles and three orthogonal polarization magnetic dipoles.

An important common point of the available MIMO antennas discussed above is the limitation of operating bandwidth. They are mostly narrow-band MIMO antennas. For example, considering relative bandwidth for voltage standing wave ratio (VSWR) less than 2, bandwidth of these MIMO antennas is limited to around 2% in [4], 4% in [9], 5% in [5], and 8.6% in [6], [7]. Obviously, they are not suitable for wideband MIMO communications. Therefore, this thesis joints a hand in developing wideband MIMO antennas and broadband MIMO antennas.

2.3.3 Mutual Coupling Reduction

As a key issue in MIMO systems, mutual coupling of elements in a MIMO antenna has received much attention. In [28], the effect of mutual coupling of elements in a fixed-length array has been investigated. The results show that, when the space between elements is smaller than $\lambda/2$, channel capacity will be significantly reduced compared to a system where mutual coupling is neglected. In MIMO antenna designs, many techniques have been reported to reduce mutual coupling in order to enhance channel capacity [29]-[35]. These techniques utilize electromagnetic band-gap (EBG) structures [29], metamaterial artificial magnetic conductor [30], defected ground structure [31], external pattern insertion [32], and network decoupling [34]-[35]. As a result of these works, element mutual couplings in a MIMO antennas are remarkably reduced. For example, an approximately 8 dB reduction of mutual coupling can be achieved in [29]. These mutual coupling reduction techniques are very promising for real MIMO

antenna applications.

2.3.4 MIMO Antennas in Advanced Systems

Recently, design of antennas for advanced wireless communication systems such as MIMO cognitive radio or UWB-MIMO is a research topic in antenna engineering. New designs of antennas for cognitive radio have been introduced in [36]-[40]. The main point of these researches is a new antenna system which combines a broadband antenna for sensing free frequency bands and some frequency reconfigurable antennas for communicating in the available band.

Another research topic related to MIMO antennas is the realization of UWB-MIMO antennas. Several UWB-MIMO antennas have been introduced [41]-[45]. In general, broadband MIMO antennas are suitable for both mentioned advanced systems. To extend knowledge in this topic, we make a contribution in developing two simple broadband antennas for MIMO cognitive radio and a compact UWB antenna for UWB-MIMO communications. The detailed investigations are presented in Chapter 4 and Chapter 5.

2.4 Chapter Summary

This chapter presented the introduction of MIMO technologies and an overview of MIMO antennas in wireless communications. We firstly illustrated the benefits of MIMO systems, compared with conventional SISO systems, that include array gain, diversity gain, spatial multiplex gain, and interference reduction. For each benefit, a brief introduction as well as explanations was presented. Furthermore, basics of MIMO systems, which involves MIMO channel modeling, and estimation of channel capacity, were also illustrated.

Finally, we also gave an overview of MIMO antennas in this chapter. The scope

of the overview included some current researches in MIMO antenna issues, such as element radiation pattern, array configuration, mutual coupling reduction techniques, and MIMO antenna in advanced systems. Some achievements and challenges have been highlighted.

Chapter 3

Wideband Compact MIMO Antennas with Tri-Polarization

3.1 Antenna Element

Before designing a MIMO antenna, it would be important to illustrate the design of antenna elements, from which the MIMO antenna is assembled. With a number of advantages such as simple design, low cost, and light weight, the printed antenna type has been used in our designs. In addition, we also design an effective balun integrated with the antenna. The balun plays an important role for widening antenna bandwidth.

An antenna element in our research is shown in Fig. 3.1. The antenna consists of two parts: a dipole and a balun microstrip. The dipole has two arms lying at two sides of a substrate. This kind of antenna has been briefly introduced in [46]. In our work, the balun was designed by gradually reducing the grounding apparatus from the connector side to the feeding point. This type of balun is similar to the cutaway balun shown in 3.2. The cutaway balun is gradually cut in a tapered fashion and transitioned into a pair of twin leads [47], [48]. In our case, the balun does not require a long transforming balun as in a coaxial cable because it is fabricated on a dielectric substrate.

Although this type of balun is simple, it can support a wide bandwidth. Detailed geometrical dimensions and characteristics of antenna elements will be presented in the next sections.



Figure 3.1: Configuration of the antenna element



Figure 3.2: Cutaway balun in [47]

Based on the antenna element above, we will introduce two designs of wideband

compact MIMO antennas which aim to achieve low mutual couplings and a wide bandwidth.

3.2 Three-port Orthogonal Polarization Antenna

3.2.1 Antenna Configuration

In this part, we propose an effective configuration of a MIMO antenna that has threeorthogonal-polarization diversity. It is called the three-port antenna. The configuration is illustrated in Fig. 3.3. Antenna elements are printed dipoles integrated with balun similar to the antenna shown in Fig. 3.1.

In order to reduce the size of the substrates while maximizing the length of the dipole, the first two antennas, named dipole 1 and dipole 2, have arms lying along the diagonal of substrates. The third one, named dipole 3, is printed dipole with a rectangular substrate as shown in Fig. 3.3(b). The three substrates are fixed by a glue that does not affect the system's performance. Ports of dipole 1, dipole 2, and dipole 3 are named port 1, port 2, and port 3, respectively.

The size of the dipoles 1 and 2 is 40 mm \times 40 mm \times 1.6 mm, whereas that of dipole 3 is 50 mm \times 40 mm \times 1.6 mm. To obtain the resonate frequency of 2.5 GHz, the lengths of the arms of dipoles 1, 2, and 3 are 23.5 mm, 24.5 mm, and 19 mm respectively. Interestingly, because of mutual coupling between the dipoles, the lengths of arms of dipoles 1, 2, and 3 are not equal.

3.2.2 Main Characteristics

The VSWR, inter-port isolation (or mutual coupling), and radiation pattern characteristics of the three-port antenna are thoroughly investigated and shown in Figs. 3.4, 3.5, and 3.6, respectively. The bandwidth of each of dipoles is over 400 MHz for VSWR



Chapter 3. Wideband Compact MIMO Antennas with Tri-Polarization

Figure 3.3: Three-port orthogonal polarization antenna: (a) dipole 1, 2; (b) dipole 3; (c) the 3-D view; (d) the practical antenna.

less than 2.0, covering a frequency band of 2.42-2.88 GHz. The relative bandwidth is over 16%. It can be seen from Fig. 3.4 that measurement and simulation data for VSWR are in good agreement. As shown in Fig. 3.5, mutual couplings are smaller

than -23 dB between ports 1, 2 and 3 over the entire frequency band. Table 3.1 shows a comparison between the three-port antenna and the antenna in [5] with highlighted parameters. In comparison with the MIMO antenna presented in [5], our proposed antennas seems much better.

Fig. 3.6 shows the measured radiation patterns in E-plane and H-plane. The dashed line represents cross-polarization whereas the solid line represents co-polarization. The radiation pattern of each port is measured with the other two ports loaded of 50 Ohm impedances. In E-plane, although the null directions of port 1 and 2 do not cor-



Figure 3.4: The VSWR characteristics of the three-port antenna

Parameter	The three-port antenna	The antenna in [5]
Material	FR4 epoxy	FR4 epoxy
Thickness of substrate	1.6 mm	1.6 mm
Center frequency	2.6 GHz	2.6 GHz
Bandwidth	16%	5%
Mutual coupling	-23 dB	-18 dB

Table 3.1: A comp	arison between	the three-po	ort antenna and	the antenna i	n [5]
-------------------	----------------	--------------	-----------------	---------------	-------



Figure 3.5: The inter-port isolation of the three-port antenna

respond to 0 degree (for port 1) nor 90 degree (for port 2) as that of the conventional dipole due to the effect from the element of port 3, the radiation patterns of port 1 and 2 are still orthogonal to each other. Furthermore, the cross-polarization levels of these ports are up to -13 dBi. In H-plane, the radiation pattern of port 3 is fairly circled, thanks to the balance effect from the other ports to two arms of the dipole 3, as shown in Fig. 3.6(f). In contrast, there is a small beam in each of th radiation patterns of port 1 and port 2 (toward +Z direction for port 2 and -Z direction for port 1) as can be seen from Figs. 3.6(b) and 3.6(d). This is because of the effect of the dipole 3 on the dipoles 1 and 2.

3.3 Cube-six-port Antenna

In [3], the MIMO cube - a compact MIMO antenna - is presented and discussed in theory. Both space and polarization diversities are utilized in the MIMO cube. All of the 12 edges of it consist of electrical dipole antennas. A large theoretical capacity



Figure 3.6: Measured cross-polarization (dashed line) and co-polarization (solid line) radiation patterns of the three-port antenna: (a) Port 1 E-plane; (b) Port 1 H-plane; (c) Port 2 E-plane; (d) Port 2 H-plane; (e) Port 3 E-plane; (f) Port 3 H-plane.

might be achieved with the cube. However, channel capacity is calculated without considering the practical issues such as mutual coupling, matching of the dipoles, or the difficulty of forming the cube. In this section, we will present a design of a practical cube consisting of six printed dipoles. The proposed cube has low mutual coupling, good matching, wide bandwidth, and simple design.

3.3.1 Antenna Design

The similar material and type of dipole as in the previous section is used. Two of the six dipoles and the configuration of the cube-six-port antenna are illustrated in Fig. 3.7. It is noted that, to achieve low mutual coupling between elements, dipoles 1, 2 and 3 in Fig. 3.7(a) are the same, whereas the dipoles 4, 5 and 6, shown in Fig. 3.7(b), are made to be the mirrored image of the dipoles 1, 2, 3. For each dipole design, the length of arm is 21.5 mm, and the substrate size is 56 mm × 56 mm × 1.6 mm. The cube has the volume of 56 mm × 56 mm × 56 mm.

3.3.2 Main Characteristics

The characteristics of the cube-six-port antenna are also investigated. The cube-sixport's simulated and measured VSWR characteristics are shown in Fig. 3.8. The cube-six-port offers a bandwidth of approximately 500 MHz for VSWR less than 2.0, covering a frequency band of 2.34-2.85 GHz. The relative bandwidth is over 16%. All VSWR curves are almost the same because of the symmetric design. Simulation and measurement are in good agreement for broadband characteristics with a small discrepancy from its centre frequency.

Fig. 3.9 illustrates the inter-port isolation between ports of the cube-six-port. Since its design is symmetric, isolation characteristics can be divided into the following groups.

- Group one, isolations between relatively close and orthogonal ports, including 1-2, 1-3, 2-3, 4-5, 4-6, 5-6, is represented by \$12.
- Group two, isolations between the same polarization ports, including 1-4, 2-5, 3-6, is represented by S14.



Figure 3.7: The cube-six-port antenna: (a) dipoles 1, 2 and 3; (b) dipoles 4, 5 and 6; (c) the 3-D view; (d) the practical cube.

• Group three, isolations between relatively far and orthogonal ports, including 1-5, 1-6, 2-4, 2-6, 3-4, 3-5, is represented by \$15.

It can be seen that mutual couplings are kept under -18 dB. As a result, elements of the cube-six-port may work independently in a MIMO system.

Radiation patterns of each port in the cube-six-port antenna are also investigated. Measured results are presented in Fig. 3.10 and Fig. 3.11 including cross-polarization (dashed line) and co-polarization (solid line). As can be seen from the figures, antenna peak gain is around 3 dBi whereas cross-polarization level is up to -5 dBi. With high cross-polarization level, the cube is suitable for MIMO applications. In E-plane, the null direction of each dipole is slightly different from that of the conventional dipole. The reason perhaps comes from the effects of elements of relatively close ports. Besides, space diversity effect can be seen from H-plane of the dipole pairs such as dipoles 1-4, 2-5, and 3-6. For instance, dipole 1 has a beam toward +Z direction in Fig. 3.10(b), whereas dipole 4 has an opposite beam in Fig. 3.11(b).



Figure 3.8: The VSWR characteristics of the cube

3.4 Wideband MIMO Experiments

Several measurements have been carried out in various environments to characterize channel capacity of MIMO systems. However, most of them are only conducted with narrowband antennas [10]- [13]. Measurements are carried in time domain at just the centre frequency of a narrow bandwidth with antennas which are not compact, and some of them are only dual-polarized. Furtheremore, an analysis of MIMO performance with general three-branch polarization diversity has been discussed in [49], but there was no specific compact MIMO antenna being mentioned. In fact, channel capacity of a wideband MIMO system utilizing real compact MIMO antennas has not received much research attention. Thus, in this work, we utilize the proposed MIMO antennas to measure channel capacity of wideband MIMO systems.

To deal with wideband antennas, we divided the band into a number of smaller



Figure 3.9: The inter-port isolations of the cube-six-port MIMO antenna



Figure 3.10: Measured cross-polarization (dashed line) and co-polarization (solid line) radiation patterns of the cube-six-port antenna: (a) Port 1 E-plane; (b) Port 1 H-plane; (c) Port 2 E-plane; (d) Port 2 H-plane; (e) Port 3 E-plane; (f) Port 3 H-plane.



Figure 3.11: Measured cross-polarization (dashed line) and co-polarization (solid line) radiation patterns of the cube-six-port antenna: (a) Port 4 E-plane; (b) Port 4 H-plane; (c) Port 5 E-plane; (d) Port 5 H-plane; (e) Port 6 E-plane; (f) Port 6 H-plane.

bandwidth. It allows us to compute the average channel capacity over a wide bandwidth. Moreover, we measure MIMO channels with different MIMO antenna configurations, and compare the effect of antenna configurations.

3.4.1 Experiment Environments

Measurements are conducted in two typical environments. One is multipath-rich Rayleigh fading environment under NLOS condition and the other is Nakagami-Rice fading (or Nakagami-m fading) environment under LOS condition. The first environment is created inside a reverberation chamber in our laboratory. The second is found in indoor environment where the multipath-rich condition is not fulfilled. Measured data in both environments will allow us to get assessment of antenna's performance in MIMO systems.

In our experiments, a four-port vector network analyzer (VNA) is used to measure the channel characteristics. Three ports of VNA are connected to elements of transmitter MIMO antenna, whereas the other port of VNA is connected alternatively to elements of receiver MIMO antenna via a coaxial switch. In the 6×6 MIMO case, we used two coaxial switches to select the respective transmitter and receiver pairs. In these experiments, all the other system's parameters, such as the array's position in the chamber and output power of the vector network analyzer, are kept unchanged. Frequency sweep in these experiments ranges from 2.45 GHz to 2.85 GHz (in the bandwidth of antennas).

3.4.1.1 The reverberation chamber environment

The reverberation chamber used in this research is a hand-made radio echoic chamber in our laboratory. It is a $4 \text{ m} \times 2 \text{ m} \times 2 \text{ m}$ chamber surrounded by six metallic walls. Fig. 3.12 shows a photograph of this chamber in our laboratory.



Figure 3.12: The reverberation chamber

The cross polarization discrimination (XPD) level inside the chamber is approximately 1.97 dB. The delay spread of the chamber is 0.6 μ sec. This chamber creates a multipath-rich environment and has NLOS characteristics due to good wave reflection inside.

Table 3.2 specifies MIMO antenna configurations including the number of elements, element spacing, and polarization diversities that are used in the experiments.

Tuble 5.2. Thitemila configuration in triffice experiments					
MIMO scheme (Tx-Rx)	Spacing (d)	Polarization (Tx-Rx)			
Com6 × Com6	Fixed	30 - 30			
Com3 × Com6	Fixed	30 - 30			
$Com3 \times Com3$	Fixed	30 - 30			
Ind6V \times Ind6V	$0.5\lambda_0$	V - V			
Ind $3V \times Ind6V$	$0.5\lambda_0$	V - V			
Ind $3V \times Ind3V$	$0.5\lambda_0$	V - V			
Ind $3V \times Ind3H$	$0.5\lambda_0$	V - H			
$Ind1V \times Ind1V$	-	V - V			

 Table 3.2: Antenna configuration in MIMO experiments



Figure 3.13: Measurement setup

A typical measurement diagram, for the 3×6 MIMO case, in which the three-port and cube-six-port MIMO antennas are at transmitter (Tx) and receiver (Rx), respectively, is presented in Fig. 3.13.

In order to compare the performance of the proposed MIMO antennas with a singlepolarization arrays, we used linearly aligned dipoles to assemble linear antenna arrays. In Table 3.2, λ_0 is the wavelength related to the centre frequency of antenna's bandwidth. In our experiments, λ_0 is equal to 120 mm. The abbreviations "3O", "V", and "H" are used to denote three-orthogonal, vertical, and horizontal polarizations, respectively. The abbreviation "Com" stands for compact MIMO antennas, whereas "Ind" represents the linear antenna array with the number of specified elements. For instance, "Com3" stands for the three-port orthogonal polarization antenna, and "Ind3V" stands for a vertically polarized linear antenna array within three individual dipoles. The same notation of MIMO schemes will be used in graphs in the followings.



(a)



Figure 3.14: Indoor experiment room: (a) a photograph of indoor experiments viewed from Rx point to Tx point; (b) the layout of the room

3.4.1.2 Indoor environment

Indoor experiments were taken in a small room in the second floor of an eight-story building at the west campus of the University of Electro-Communications. This building, which contains laboratories and some small offices, was built from brick and steelreinforced concrete walls, like many other modern constructions. The size of experiment room is 6.5 m \times 3.6 m \times 2.5 m (Length \times Width \times Height). In order to reduce the reflected paths, we kept the room empty except the antenna and cable systems. The layout of the experimental room and a photograph of it are presented in Fig. 3.14.

Experiments in the indoor environment are carried out at the transmitter point (Tx) and receiver point (Rx) as shown in Fig. 3.14(b) (example in the case of Com6 \times Com6). Antennas are placed so that respective elements of transmitter and receiver antennas have a same polarization. Antennas are set at 1m-height from the floor of the experimental room and configurations are listed in Table 3.2.

3.4.2 Channel Characteristics

3.4.2.1 Channel matrix normalization

The channel matrix $\mathbf{A}(f)$ is defined as discussed in Chapter 2. Because the average received power changes in different measurements due to different environments (e.g. reverberation chamber or indoors) and different antenna configurations, it is necessary to normalize channel matrices in order to compare channel characteristics (such as CDFs of eigenvalues) and channel capacity. There are many types of matrix normalizations depending on the purpose of comparison [1]. In our study, for all systems with the same number of branches, a normalization factor will be calculated from the measured data of a reference system which employed vertically polarized antenna configurations. The channel matrices of reference systems will be normalized in such a manner that the power transferring between single transmitter and receiver antennas, on average, is normalized to be unified. For instance, all 3×3 MIMO systems in the same environment will have the same normalization factor computed from "Ind3V × Ind3V" with spacing $0.5\lambda_0$ in table 3.2. This is because the main difference between the conventional single polarization system with the same number of branches comes from the

MIMO scheme (Tx-Rx)	Reference	Chamber	Indoor
6 × 6	Ind6V x Ind6V	0.0379	0.0066
3 × 6	Ind3V x Ind6V	0.0366	0.0067
3 × 3	Ind3V x Ind3V	0.0377	0.0064
1 × 1	Ind1V x Ind1V	0.0369	0.0059

Table 3.3: Normalization factors (N_F)

cross-polarization discrimination (XPD) [2].

Let $\mathbf{A}^{(m)}$ and $\overline{\mathbf{A}}^{(m)}$ stand for the measured and normalized matrices, respectively, where the superscript represents the m^{th} sample of the matrix in the frequency domain. Let N_F represent the normalization factor. The equation between $\overline{\mathbf{A}}^{(m)}$ and $\mathbf{A}^{(m)}$ will be expressed as

$$\overline{\mathbf{A}}^{(m)} = N_F \mathbf{A}^{(m)}. \tag{3.1}$$

The normalization factor is determined by

$$\frac{1}{MN_t N_r} \sum_{m=1}^{M} \sum_{r=1}^{N_r} \sum_{t=1}^{N_t} \left| N_F a_{rt_vv}^{(m)} \right|^2 = 1$$
(3.2)

where *M* is the number of matrix samples in the frequency range and $a_{rt_v}^{(m)}$ is the $a_{rt}^{(m)}$ of the reference systems which employed only vertically polarized antenna configurations.

Solving (3.2), the normalization factor can be obtained as

$$N_F = \sqrt{\frac{N_t N_r}{\sum_{r=1}^{N_r} \sum_{t=1}^{N_t} \left\langle |a_{rt_{-}\mathbf{v}\mathbf{v}}|^2 \right\rangle}}.$$
(3.3)

The values of N_F for different antenna configurations are presented in Table 3.3.



Figure 3.15: Typical received signals

All systems with a same number of braches will have the same value of normalization factor. For the same environment, these values are nearly equal, whereas for the same MIMO configuration, the value in the reverberation chamber is greater than that in indoor environment due to higher received power.

3.4.2.2 Channel characteristics

Fig. 3.15 illustrates some typical received signals in different environments and polarizations. These signals are obtained when the transmitter antenna is set to vertical polarization and the receiver antenna is set to vertical and horizontal polarizations in succession. In the reverberation chamber, since the XPD level is quite small, the difference in received signal levels between vertical and horizontal polarizations is not much. In contrast, in indoor environments, received signal levels in different polarizations are



Figure 3.16: PDFs for the magnitude of normalized received signals

clearly different due to high XPD value (of about 13dB in our experiments).

The probability density functions (PDFs) for the magnitude of normalized received signals are also computed. Fig. 4.16 shows the obtained PDFs for "Ind6V × Ind6V" configuration in the considered environments. The PDF for normalized received signals in the chamber is compared with the ideal Rayleigh distribution with parameter $\sigma^2 = 0.5$, whereas the value for the indoor environment is compared with the ideal Nakagami-m distribution with parameters m = 1.6149 and $\omega = 1$. The parameters, σ , m, and ω , are determined from the measured results. The value $2\sigma^2$ in Rayleigh distribution and ω in Nakagami-m distribution are represented the averaged transmission power [50]. From the normalization method, we normalized averaged transmission power as 1 (Eq. 3.2). Therefore, $2\sigma^2$ and ω should be equal to 1. The value m is calculated from Nakagami-m distribution [50] as

$$m = \frac{(\overline{R^2})^2}{(\overline{R^2} - \overline{\overline{R^2}})^2}$$
(3.4)

where R is magnitude of normalized received signals obtained from measurement.

The CDFs of measured and theoretical eigenvalues for "Com3 \times Com3", "Com3 \times Com6" and "Com6 \times Com6" MIMO in the chamber and indoor environments are plotted in Fig. 3.17, Fig. 3.18, and Fig. 3.19 respectively.

From Fig. 3.17, Fig. 3.18, and Fig. 3.19, we can see that the respective eigenvalues λ_1 , λ_2 and λ_3 in the 6 × 6 MIMO are greater than those in 3 × 6 and 3 × 3 MIMO. Those values in 3 × 3 MIMO are the smallest among these MIMO systems. This is because MIMO systems rely on the environment to produce uncorrelated signals at the receive antennas. If the number of transmitting antennas is fixed and the number of receiving antennas is increased, the probability that uncorrelated signals can reach the receiver will increase. Therefore, among MIMO systems having the same number of transmitting antennas will have higher eigenvalues.

Moreover, in environments with LOS propagation like the indoor setup, respective eigenvalues in the considered configurations are smaller than those in the reverberation chamber on a given value of cumulative probability. The reason principally comes from the low received power for cross-polarization component due to the high XPD in the indoor environment.

3.4.3 Channel Capacity

In this thesis, the main target is to propose novel MIMO antennas and examine them in MIMO environments. To simplify in calculation, we assume that CSI is available not only receiver side but also transmitter side.



Figure 3.17: CDFs of normalized eigenvalues for MIMO systems with the "Com3 \times Com3" configuration in difference environments: (a) reverberation chamber; (b) Indoor.



Figure 3.18: CDFs of normalized eigenvalues for MIMO systems with the "Com $3 \times$ Com6" configuration in different environments: (a) reverberation chamber; (b) Indoor.



Figure 3.19: CDFs of normalized eigenvalues for MIMO systems with the "Com $6 \times$ Com6" configuration in different environments: (a) reverberation chamber; (b) Indoor.

With the normalization discussed in Section 3.3.2, calculation of averaged channel capacity involves the effects of path loss in each MIMO scheme. Averaged channel capacity given in bps/Hz is computed at different SNR values.

The difference between systems with tri-polarization antennas and with the single polarization array will be explored by estimating the polarization effect in Section 3.4.3.1. The averaged channel capacity in different number of antennas (including two types of tri-polarization antennas) will be investigated in Section 3.4.3.2. Notations in Table 3.2 are used in the following graphs.

3.4.3.1 The effect of polarization

Polarization is one of the most important factors that affect channel capacity. In this section, we measured for 3×3 MIMO systems. We considered both co-polarization ("Ind3V × Ind3V") and cross-polarization ("Ind3V × Ind3H") systems. In addition, the "Com3 × Com3" MIMO system which employed the three-port orthogonal polarization antennas is also measured. Channel capacity for these systems is presented in Fig. 3.20.

In the co-polarization system, the received signal level is higher than that in the cross-polarization system, mainly due to XPD in the environment [2]. Therefore, channel capacity of the co-polarization system is higher than channel capacity of the cross-polarization as shown in Fig. 3.20. Channel capacity in the compact MIMO system is greater than that in the cross-polarization system, but lower than that of the co-polarization system. The difference between channel capacity of these systems depends on different environments.

3.4.3.2 The effect of the number of antennas

To explore channel capacity in systems which employed the proposed compact MIMO antennas, we measured "Com6 \times Com6", "Com3 \times Com6" and "Com3 \times Com3"



Figure 3.20: Averaged channel capacity for different polarization diversities: (a) In reverberation chamber; (b) In Indoor.



Figure 3.21: Averaged channel capacity for different antenna number: (a) In reverberation chamber; (b) In Indoor.

MIMO systems. In order to compare with the conventional single polarization systems, MIMO systems with "Ind6V × Ind6V", "Ind3V × Ind6V", "Ind3V × Ind3V", and "Ind1V × Ind1V" are also measured. The channel capacity is shown in Fig. 3.21 in all the considered environments. As can be seen from the figure, the compact MIMO systems provide high channel capacity, particularly in the multipath-rich environment like the reverberation chamber. The highest capacity in these systems can be achieved from the implementation of the cube-six-port antenna. Also, channel capacity of "Com3 × Com6" MIMO is much higher than that of "Com3 × Com3" MIMO. These measured data demonstrate that the proposed compact MIMO antennas work well in MIMO systems and promise to achieve high channel capacity in real applications.

3.5 Chapter Summary

This chapter focused on the designs of two novel, wideband, compact MIMO antennas for MIMO wireless communications. One is the three-port MIMO antenna, whereas the other is a cube-six-port MIMO antenna which has both polarization and space diversities. These antennas achieved a bandwidth over 16% at the centre frequency of 2.6 GHz. Mutual couplings between ports of the antennas are below -20 dB and -18 dB for three-port and cube-six-port antennas respectively. The size is only 40 mm × 40 mm for the three-port antenna and 56 mm × 56 mm × 56 mm for the cube-six-port antenna at the centre frequency of around 2.6 GHz.

We also presented the results of measurements for MIMO systems which employed the proposed antennas in a multipath-rich environment and an indoor channel. Measured data were processed in order to examine the channel characteristics such as received signal level or CDFs of eigenvalues. Detailed explanations in data normalization or theoretical calculations of PDFs for i.i.d. Rayleigh fading environment for 3×3 or 3×6 MIMO cases were also presented. Furthermore, the effects of the configurations of compact MIMO antennas and linear antenna arrays on channel capacity were investigated. High capacity can be achieved from the MIMO systems which employed the proposed compact MIMO antennas.

Chapter 4

Broadband Antennas for MIMO Cognitive Radio

4.1 Broadband Antenna Design

In the previous chapter, we introduced two MIMO antennas that offer a bandwidth of 16%. These antennas are applicable to wideband MIMO communications. However, a wider bandwidth (broadband) may be required in advanced systems such as MIMO cognitive radio. Therefore, design of broadband MIMO antennas would be an important work. On the other hand, most of designs of available broadband antennas are complex and large [51]-[59]. Thus, they are not suitable to form a compact broadband MIMO antenna.

In this section, we propose a simple, compact antenna that offers a broad bandwidth, good gain, and high cross-polarization levels. This antenna will be used as elements of broadband MIMO antennas for MIMO wireless communication systems. The antenna configuration is presented before some main antenna characteristics are shown and discussed.



(c)

Figure 4.1: Configuration of the antenna: (a) layout geometry, (b) front view of the prototype, (c) back view of the prototype

4.1.1 Antenna Configuration

In order to enhance the antenna bandwidth, we integrate a dipole with a parallel transmission line. The arms of the dipole as well as parts of the transmission line are assembled in different sides of the antenna substrate. The configuration of the proposed antenna is shown in Fig. 4.1.

The antenna has three parts: a grounding component, the parallel transmission line, and the dipole. The antenna is designed and fabricated on an FR4 epoxy substrate (relative permittivity is 4.5). The thickness of the substrate is 1.6 mm. Simulation is


Figure 4.2: Width of substrate (l = 20.5 mm, d = 28 mm)

conducted by using the Ansoft HFSS software.

4.1.2 **Operation Principle**

Since the transmission line is designed to be closed to the dipole, there will be a strong coupling between the bottom-side line of the transmission line and the bottom-side arm of the dipole, particularly at low frequency region. This mutual coupling will make the currents on the transmission line unbalance. Therefore, even though the transmission line is designed as a feeding line for the dipole, it will also act as a radiation source at low frequency region. At high frequency region, on the other hand, the mutual coupling is weak; therefore, the main radiation source would be the dipole only. The combination of the transmission line and the dipole would result in expanding the antenna bandwidth.



Figure 4.3: Length of dipole arm (y = 15 mm, d = 28 mm)



Figure 4.4: Width of grounding part (y = 15 mm, l = 20.5 mm)

4.1.3 Key Parameter Studies

We intend to propose a broadband antenna operating at the frequency of wireless applications such as WiMAX or WIFI with cognitive radio. Therefore, antenna geometrical parameters are determined so that the resonated frequencies should be from 2 GHz to 11 GHz as suggested in the IEEE 802.16a standard [60]. The geometrical parameters

Parameter	Notation	Value
Length of substrate	x	80
Width of substrate	у	15
Length of dipole arm	l	20.5
Width of grounding part	d	28
Width of dipole arm	w	3
Width of feeding line	а	1

Table 4.1: The optimum geometrical parameters (mm)

of the antenna are optimized through simulation. As a result, we achieved a desired antenna, which offers a broad bandwidth, extending from 2.3 GHz to about 4.0 GHz, for VSWR less than 2. For that bandwidth, the length of the substrate is equal to 80 mm. In this section, we highlight the effects of some key parameters by successively adjusting them while keeping the others unchanged in simulations.

Dependence on 'y': The width of substrate plays an important role for antenna performance. It represents the distance between the transmission line and the dipole, therefore, affects to the coupling of them. When equal to 15 mm for l = 20.5 mm and d = 28 mm, it supports the most suitable matching and broad bandwidth as shown in Fig. 4.2.

Dependence on 'l': Fig. 4.3 shows the VSWR characteristics with different values of *l*. As can be seen from the figure, the length of dipole arm affects strongly to the bandwidth of antenna. The value *l* is chosen equal to 20.5 mm for y = 15 mm and d = 28 mm, as it is the most appropriate for matching and wide bandwidth target.

Dependence on 'd': Fig. 4.4 illustrates the VSWR of the antenna when changing the width of grounding part and keeping y = 15 mm and l = 20.5 mm. For *d* equal to 28 mm, couplings between the dipole, the transmission line and the ground will play the best role for expanding antenna bandwidth.

Table 5.1 lists the optimized parameters of the proposed antenna. The other param-



Figure 4.5: Simulated vector surface current distribution on the proposed dipole: (a) 2.3 GHz; (b) 3.2 GHz; (c) 3.9 GHz.

eters may also affect the antenna performance but not much.

4.1.4 Current Distribution

The vector current distribution of the antenna is shown in Fig. 4.5 at three frequencies in the antenna bandwidth: the lowest, the centre and the highest frequencies. As can be seen from the figure, the values of currents on the transmission line are unbalance. The reason comes from the strong coupling between the bottom-side arm of the antenna and the bottom-side line of the transmission line, particularly at the low frequency region of the antenna bandwidth. Therefore, the line acts as an extra-antenna, resulting in widening the bandwidth of conventional dipole.

4.1.5 Measurement Results

Fig. 4.6 shows the simulated and measured results of the antenna VSWR. As can be seen from the measured data, the antenna offers a bandwidth of 50.62% extending from approximately 2.4 GHz to 4.0 GHz with the centre frequency of 3.2 GHz, for



Figure 4.6: Antenna VSWR characteristic



Figure 4.7: Measured antenna peak gain in XY plane

VSWR less than 2. The measured results almost agree with the simulated ones for broadband characteristic with a small discrepancy of its centre frequency (3.1 GHz for simulated and 3.2 GHz for measured). This discrepancy comes from the reduction of the substrate thickness due to removing unwanted copper layer when manufacturing the antenna.



Figure 4.8: Measured cross-polarization (dashed line) and co-polarization (solid line) radiation patterns of the antenna: (a) E-plane 2.4 GHz; (b) H-plane 2.4 GHz; (c) E-plane 3.2 GHz; (d) H-plane 3.2 GHz; (e) E-plane 4.0 GHz; (f) H-plane 4.0 GHz.

The antenna also offers good peak gains as shown in Fig. 4.7. In its entire bandwidth, antenna gain varies from about 0.2 dBi to 4.5 dBi. The maximum gain can be achieved at 2.45 GHz. This value is much better than that of a conventional half-wave dipole.

The radiation patterns are examined at the lowest, the centre and the highest frequencies in antenna bandwidth. Fig. 4.8 shows the measured radiation patterns of the proposed antenna at 2.4 GHz, 3.2 GHz, and 4.0 GHz in E-plane (XY plane) and H-plane. As can be seen from the graphs, the proposed antenna has radiation patterns similar to that of the conventional half-wave dipole. In high frequency region, currents on the grounding part, as can be seen from Fig. 4.5, may affect to the performance of the dipole. This results in the distorting radiation pattern of the antenna in H-plane at 4 GHz.

Cross-polarization levels (dashed line) of the proposed antenna can be achieved up to -5 dBi. This is supportive for MIMO systems working in multipath environments where cross polarization discrimination (XPD) of the channel may degrade to be 0 dB or so.

4.2 Broadband MIMO Antennas

In this section, we propose two simple broadband MIMO antennas for MIMO applications in cognitive radio. One is a two-port MIMO antenna and the other is a four-port MIMO antenna. The elements of these MIMO antennas are based on the antenna proposed in Section 4.1.



Figure 4.9: The configuration of two-port MIMO antenna

4.2.1 Two-Port MIMO Antenna

4.2.1.1 Configuration

The configuration of the two-port MIMO antenna is illustrated in Fig. 4.9. This design consists of two antennas placing along the longer dimension of a rectangular substrate. The material and geometrical parameters of each antenna element are as equal as those of the proposed in section 4.1. To achieve an acceptable mutual coupling level between the two ports while keeping the MIMO antenna simple and compact, we cut off the substrate and copper layers in the middle of elements. It is expected that a better performance of the MIMO antenna may be achieved by utilizing some techniques in the middle space to reduce mutual coupling. However, by doing this, the design of the MIMO antenna may be more complex. This will be reported in our future works. The overall volume of the two-port MIMO antenna is 80 mm \times 40 mm \times 1.6 mm as shown in Fig. 4.9.



Figure 4.10: VSWR characteristics of the two-port MIMO antenna

4.2.1.2 Main Charateristics

Fig. 4.10 shows the measured VSWR characteristics for the ports of the MIMO antenna. Because of the symmetric design, the VSWR curves are almost the same. From this figure, we can see the MIMO antenna offers a bandwidth of over 50% for VSWR less than 2, extending from 2.39 GHz to 3.92 GHz. The VSWR characteristics of antenna elements in the MIMO antenna are as similar as those of the antenna proposed in Section 4.1.

Mutual coupling (inter-port isolation) between the ports is one of the most important parameters of a MIMO antenna. The measured mutual coupling characteristic of two ports of the MIMO antenna is shown in Fig. 4.11. As can be seen from the figure, the worst level of mutual coupling is about -10 dB at the low frequency region of the bandwidth. At the higher frequency part, it is only around -20 dB. The low mutual coupling suggests a good performance of the MIMO antenna in a real MIMO application in cognitive radio.



Figure 4.11: Inter-port isolation of the two-port MIMO antenna

4.2.2 Four-Port MIMO Antenna

4.2.2.1 Configuration

In this section, we propose a four-port MIMO antenna in which not only space but also polarization diversities are utilized. The antenna consists of four same broadband antennas, placed in the edges of a square substrate. The configuration of the antenna and its parameters for one side is shown in Fig. 4.12. The overall volume of the antenna is 80 mm \times 80 mm \times 1.6 mm. Similar to the two-port MIMO antenna, the center of this four-port MIMO antenna is cut off to achieve acceptable coupling levels.

4.2.2.2 Main Charateristics

Fig. 4.13 shows the measured VSWR characteristics of the four-port MIMO antenna. Again, because of the symmetric design, the VSWR curves are almost the same. As can be seen from the data, the four-port MIMO antenna offers an absolute bandwidth of 1.79 GHz for VSWR less than 2, extending from 2.29 GHz to 4.08 GHz, corresponding to 56.2% relative bandwidth. The bandwidth is slightly wider than that of the two-port



Figure 4.12: The configuration of the four-port MIMO antenna

MIMO antenna. The reason may come from the incorrect modeling of connectors since they are relatively closed to the arm of orthogonal elements.

We also measured the mutual coupling characteristics between ports of the MIMO antenna. The measured results are shown in Fig. 4.14. In this figure, 'isolation 1-2' represents the mutual coupling between ports having a same polarization whereas 'isolation 1-3' represents that of orthogonal ports. Here, at low frequencies of the bandwidth, mutual coupling is kept under -10 dB whereas at the high frequencies, it is under -20 dB, particularly between orthogonal ports. The proposed MIMO antennas (the two-port and the four-port) emphasize the simple figure of the broadband antenna element. They not only fulfill the request of low mutual coupling for MIMO systems but also respond to the demand on wideband for cognitive radio operations.



Figure 4.13: VSWR characteristics of the four-port MIMO antenna



Figure 4.14: Inter-port isolation of the four-port MIMO antenna

4.3 Broadband MIMO Experiments

Since the proposed MIMO antenna offer a broad bandwidth, operation of MIMO systems utilizing them may be different between sub-channels. Therefore, it would be interesting to examine the change of channel capacity on frequency in the whole an-



Figure 4.15: Experiment chamber

tenna bandwidth. To make our work simple, we conducted MIMO experiments in the reverberation chamber, which supports multipath-rich propagation.

4.3.1 Environment and Experiment Setup

4.3.1.1 Experiment Environment

We utilized both the four-port MIMO antenna and the two-port MIMO antenna to have variations of 2×2 , 2×4 , and 4×4 MIMO configurations in experiments. The typical 2×4 MIMO scheme is shown in Fig. 4.15, where the two-port MIMO antenna is at the transmitter and the four-port MIMO antenna is at the receiver. The same reverberation chamber as presented in Section 3.3.1 was used in these experiments.

4.3.1.2 Experiment Setup

The operating bandwidth of the broadband MIMO antennas is around 1.7 GHz, extending from 2.3 GHz to 4.0 GHz. In order to analyze MIMO operation in a broad bandwidth, we measure channel characteristics on a frequency band, varying from 2 GHz to 4.5 GHz. We divide this band into 20 sub-bands (or sub-channels), in which each sub-band accounts for 125 MHz. Furthermore, each sub-band is divided into 1000 sub-bands. Our purpose is to examine the averaged channel capacity in each sub-band. We use a vector network analyzer to measure channel characteristics as a function of frequency f.

Considering the channel matrix $\mathbf{A}(f)$ as defined in Chapter 2, in these experiments, we will measure the values $a_{rt}(f)$ for MIMO configurations. Since we have a number of sub-channels, measured data should be normalized in order to allow comparisons between their performances over the frequency range. The 10th sub-channel which locates at the center of the examined band will be used as a reference. We employed the Frobenius normalization, in which the averaged power, at the 10th sub-channel, is normalized to unity. The normalization factor calculated from measured data of this sub-channel is used to normalize every sub-channel of the same MIMO configuration. By doing so, we keep the dependence of antenna parameters such as antenna gain, VSWR, or radiation patterns on frequency along the considered band.

Again, let \mathbf{A} , $\overline{\mathbf{A}}$, and N_{F10} stand for the measured matrix, normalized matrix, and the normalization factor (calculated from the 10th sub-channel) respectively. $\overline{\mathbf{A}}$ is given as

$$\overline{\mathbf{A}(\mathbf{f})} = N_{F10}\mathbf{A}(\mathbf{f}). \tag{4.1}$$

The normalization factor is calculated as

$$N_{F10} = \sqrt{\frac{N_t N_r}{\sum_{r=1}^{N_t} \sum_{t=1}^{N_t} \left\langle |a_{rt10}|^2 \right\rangle}}$$
(4.2)

where a_{rt10} represents a_{rt} in the 10th sub-channel.

We computed the probability density functions (PDFs) for the magnitude of the



Figure 4.16: PDFs for the magnitude of normalized received signals in different subbands

normalized received signals to character the measurement environment. Fig. 4.16 shows the obtained PDFs for the 4 × 4 MIMO configuration in some typical subchannels: the 4th sub-band (from 2.375 GHz to 2.500 GHz), the 10th sub-band (from 3.125 GHz to 3.250 GHz), and the 16th sub-band (from 3.875 GHz to 4.000 GHz). The PDFs for the normalized received signals are compared with the ideal Rayleigh distributions with parameters σ^2 determined from the normalization method, and measured data. While we normalized the averaged transmission power ($2\sigma^2$) as one, the value σ^2 for the 10th sub-channel should be equal to 0.5. Moreover, the values for other sub-channels are calculated from measured data after normalization procedures. For example, the values σ^2 for the 4th and the 16th sub-channels are equal to 0.645 and 0.504 respectively. As can be seen from Fig. 4.16, the PDF for the normalized signals and the i.i.d theoretical are in good agreement since the reverberation chamber creates a multipath-rich environment with non-line-of-sight (NLOS) condition.

Considering sub-channels inside the antenna bandwidth, we found that most of the PDFs for normalized signals are similar with that in the 10th sub-channel. The 16th sub-band is a typical of them. However, there are still some sub-channels, for example the 4th sub-channel, in which PDFs are different from that in the 10th sub-channel. The reason comes from the dependence of antenna performance and wave propagation on frequency in a wide range.

4.3.2 Correlation Parameter

In Section 4.2, we considered mutual coupling between elements of MIMO antennas: Fig. 4.11 for the two-port MIMO antenna and Fig. 4.14 for four-port MIMO antenna. Thanks to low mutual coupling between elements, we expect that antenna elements in MIMO antennas work independently in MIMO systems. To verify this, in this section, we calculate the averaged correlation coefficient from the measured data which include spatial correlation effect due to multipath propagation.

Theoretically, correlation matrices at receiver side $\mathbf{R}_{\mathbf{Rx}}$ and transmitter side $\mathbf{R}_{\mathbf{Tx}}$ can be calculated as [21], [61], [62]

$$\mathbf{R}_{\mathbf{Tx}}(f) = \mathbf{A}^{\mathrm{H}}(f)\mathbf{A}(f) \tag{4.3}$$

and

$$\mathbf{R}_{\mathbf{R}\mathbf{x}}(f) = \mathbf{A}(f)\mathbf{A}^{\mathrm{H}}(f) \tag{4.4}$$

where H denotes the Hermitian operator.

In our work, we will calculate averaged correlation coefficient for every sub-channel as a frequency average over sub-sub-channels. For example, averaged correlation matrix at receiver side of a sub-channel is computed as

$$\overline{\mathbf{R}}_{\mathbf{Rx}} = \frac{1}{K} \sum_{k=1}^{K} \mathbf{A} \left(f_{submin} + (k-1) \Delta f \right) \mathbf{A}^{\mathrm{H}} \left(f_{submin} + (k-1) \Delta f \right)$$
(4.5)

where *K* is the number of sub-sub-channels in a sub-channel, f_{submin} is the lowest frequency of each sub-band, and Δf is bandwidth of sub-sub-channels. In our experiments, *K* equals to 1000 and Δf equals to 125 KHz.

It is noted that the diagonal elements of correlation matrix are real values. With a sufficient number of K, the values of diagonal elements of averaged correlation matrix of each sub-channel are almost equal because they represent the averaged power of propagation paths. Therefore, normalized averaged correlation matrix will be calculated as

$$\overline{\mathbf{R}}_{\mathbf{Rx}}^{norm} = \frac{N\overline{\mathbf{R}}_{\mathbf{Rx}}(f)}{\operatorname{tr}\{\overline{\mathbf{R}}_{\mathbf{Rx}}(f)\}}$$
(4.6)

$$\cong \left\{ \begin{bmatrix} 1 & \rho_{12} & \rho_{13} & \rho_{14} \\ \rho_{21} & 1 & \rho_{23} & \rho_{24} \\ \rho_{31} & \rho_{32} & 1 & \rho_{34} \\ \rho_{41} & \rho_{42} & \rho_{43} & 1 \end{bmatrix} \quad \text{for } N = 4 \\ \begin{bmatrix} 1 & \rho_{12} \\ \rho_{21} & 1 \end{bmatrix} \quad \text{for } N = 2 \end{bmatrix} \right\}$$

where N is equal to N_r , $tr{\overline{\mathbf{R}}_{\mathbf{Rx}}(f)}$ is the trace of matrix ${\overline{\mathbf{R}}_{\mathbf{Rx}}(f)}$, and $\rho_{ij(j\neq i)}$ is complex correlation coefficient. The averaged power correlation coefficient $\hat{\rho}_p$ can be cal-



Figure 4.17: Correlation coefficient of sub-channels

culated as [63]

$$\hat{\rho}_p = \frac{1}{N(N-1)} \sum_{i=1}^{N} \sum_{\substack{j=1\\j\neq i}}^{N} \left| \rho_{ij} \right|^2.$$
(4.7)

From the measured data, we calculated the averaged power correlation coefficient at receiver side $\hat{\rho}_p$ as expressed in Eq. (4.7) for the considered MIMO configurations. Fig. 4.17 illustrates the correlation coefficient calculated for every sub-channel. As can be seen from this figure, the correlation coefficient is kept under 0.1 in the whole range of the examined frequency band. In the low frequency region, the correlation coefficient is slightly higher than that in the high frequency region. This is because the mutual couplings between antenna elements of MIMO antennas are below -10 dB at low frequency band, and below -20 dB at high frequency band as shown in Fig. 4.11 and Fig. 4.14. Thanks to very small correlation coefficients, channel capacity of sub-channels will not be much affected from antenna mutual coupling. Moreover,



Figure 4.18: Channel capacity (SNR = 10 dB)

similar results of correlation coefficients in transmitter side can be easily achieved by expression in Eq. (4.7) and measured data.

4.3.3 Channel Capacity Estimation

The goal of this section is estimating the change of channel capacity of MIMO systems over the considered frequency range. This is much interesting for real MIMO applications in cognitive radio, where operating frequency must be switched to available channels in a wide frequency range. The estimation is undertaken from the averaged capacity of sub-channels from measured data. Averaged channel capacity is computed at the SNR value of 10 dB.

Fig. 4.18 presents a comparison of averaged channel capacity in the measured frequency band. It can be seen that, for the all MIMO configurations, channel capacity almost remains unchanged inside the bandwidth of the MIMO antennas (from 2.3 GHz to 4.0 GHz), whereas channel capacity is reduced outside of the bandwidth. It is because of the impedance matching issues of antennas since VSWR values outside the MIMO antenna bandwidth significantly increases as shown in Fig. 4.10 (the two-port MIMO antenna) and Fig. 4.13 (the four-port MIMO antenna). Therefore, outside the bandwidth, MIMO antennas do not operate as well as its performance inside the bandwidth.

Furthermore, at around 2.5 GHz, the channel capacity is slightly higher than at other frequencies. The reason comes from both dependence of wave propagation characteristics of the reverberation chamber and the dependence of antenna performance on frequency. The first reason has a strong effect to channel capacity in a wide examined frequency range. It would be the main reason in this case. In fact, the reverberation chamber in our laboratory is a hand-made radio echoic chamber that supports multipath-rich wave propagation. However, wave propagation characteristics (attenuation or time spread) are frequency dependent. In low frequency region, attenuation of wave propagation is smaller than that in high frequency region, therefore, receive power is greater ($\sigma^2 = 0.645$ as shown in Fig. 4.16). As a result, channel capacity of sub-channel in this frequency region is slightly higher.

The second reason is because of the dependence of antenna performance on frequency. This is not primary reason, however, in term of antenna gain, we can see in Section 4.1.5 that the peak gain of 4.5 dBi can be achieved at around 2.45 GHz. In addition, in term of impedance matching, good matching of the MIMO antennas can be obtained at around 2.5 GHz as illustrated in Fig. 4.10 (the two-port MIMO antenna) and Fig. 4.13 (the four-port MIMO antenna) whereas outside the bandwidth, MIMO antennas are mismatched. Furthermore, among the three MIMO configurations, the 4×4 scheme offers the highest whereas the 2×2 scheme provides the lowest system capacity. This is a well-known knowledge and predictable for MIMO systems with normal antennas. However, from the view point of new antenna designing, these results confirm that our proposed antennas work well in particular systems. Moreover, it means the proposed broadband antenna element is not only simple but also very effective.

4.4 Chapter Summary

In this chapter, we proposed a simple and compact broadband antenna. Detailed explorations are conducted to analyze the performance of the antenna. The antenna offers a relative bandwidth of over 50% for VSWR less than 2, extending from approximately 2.4 GHz to 4.0 GHz with the centre frequency of 3.2 GHz. Compared with the conventional dipole, the proposed antenna also has high gain and cross polarization level characteristics.

In additional, we proposed two simple broadband MIMO antennas that are designed based on the proposed broadband antenna. Measured results show that these MIMO antennas also have a relative bandwidth of over 50%. Mutual coupling is kept under -10 dB at low frequencies and under -20 dB at high frequencies in the bandwidth of the MIMO antennas.

We also conducted some MIMO experiments in a reverberation chamber in a wide range of frequency to examine the change of channel capacity over a wide frequency range. It has been pointed out that, in all the considered MIMO configurations, the channel capacity mostly remains unchanged in the bandwidth of the MIMO antennas. This result is very important for MIMO systems in cognitive radio since they have to change working frequency during their operation. Thanks to good characteristics, both the proposed broadband antenna and the MIMO antennas are promising for MIMO applications in cognitive radio.

Chapter 5

A Compact UWB Antenna

5.1 Introduction of UWB antennas

Ultra-wideband (UWB) technology, which migrates over wide range of frequency bands from 3.1 GHz to 10.3 GHz, has received a number of attentions in recent times. Its devices employ very narrow or short duration pulses, therefore, requires such a wideband transmission bandwidth. It is believed that UWB technology would be a key factor for advanced wireless communication systems such as UWB-MIMO, which may offer a data rate of more than 1 Gb/s [41]. Since UWB technique is still in its initial research adventure, UWB antenna currently has been an attractive topic.

Recently, several UWB antennas have been introduced [64]-[71]. However, overcoming the complexity and large size of antenna configurations are still a challenging for antenna engineers. The size of printed UWB antennas are usually around 40 mm \times 50 mm to 25 mm \times 25 mm [64]-[66]. Furthermore, most of available UWB antenna are slot antennas [70] or patch antennas with different modified sharps of patch and feeding configuration [64]-[69].

In this chapter, we present a novel UWB antenna which is based on the printed dipole type. The size of the proposed antenna is only $9 \text{ mm} \times 57.5 \text{ mm} \times 1.6 \text{ mm}$. Al-



Figure 5.1: Geometry of proposed antenna



Figure 5.2: Photograph of the fabricated antenna.

though antenna length is slightly long, its width is one of the narrowest among available UWB antennas. With such compact dimension, the antenna can be easily located inside a small volume. Furthermore, thanks to the simple design and compact size of the proposed UWB antenna, it is expected that some UWB-MIMO antennas, assembled from the proposed UWB antenna, can be achieved for UWB-MIMO communications.

5.2 Compact UWB Dipole Antenna

5.2.1 Antenna Design

Fig. 5.1 illustrates the configuration of the proposed antenna, of which components are etched onto a piece of printed circuit board. The substrate material is FR4 epoxy that has a relative permittivity of 4.4 and loss tangent of 0.02. The thickness of substrate is 1.6 mm. The antenna mainly consists of four parts: a dipole, a grounding component,

Parameter	Notation	Value
Length of dipole arm	т	10.5
Width of grounding part	<i>d</i> 1	8.5
Length of loaded patch	d2	21
Space between grounding part and dipole arm	<i>s</i> 1	3.5
Space between load patch and dipole arm	<i>s</i> 2	3
Width of transmission line	a	0.5
Width of dipole arm	w	2
Length of feeding strip	р	4
Width of feeding strip	q	1.5
Width of substrate	n	9
Length of substrate $(d1 + s1 + 2m + a + s2 + d2)$	_	57.5

Table 5.1: The optimum geometrical parameters (mm)

a transmission line feeding the dipole, and a patch. The arms of the dipole and two lines of the transmission line are assembled at different sides of the antenna substrate, similar to our previous work [72]. However, instead of a parallel transmission line as in [72], in this design, there is a vertical deflection between lines of the transmission line. The reason is to make currents on the lines more unbalanced, so that the transmission line can act as a radiator even it is designed to feed the dipole. In addition, we design a patch located at the end of the transmission line. The mutual coupling between the patch and the top-side arm of the dipole also plays an important role to make currents on the transmission line unbalanced. The geometrical parameters, optimized to obtain the possible largest bandwidth for VSWR less than 2, are listed in Table 5.1.

5.2.2 Results and Discussion

The proposed antenna has been manufactured in our university. Photographs of the proposed antenna are shown in Fig. 5.2 with front and back views. The size of the



Figure 5.3: Measured and simulated VSWR of the proposed antenna

antenna is compared with the size of a 500-JPY coin. We measured the manufactured antenna by a vector network analyzer in an anechoic chamber. Fig. 5.3 shows the comparison of the simulated and measured VSWR characteristics of the antenna. As can be seen from Fig. 5.3, the measured bandwidth for VSWR less than 2 covers the frequency range of 3.5-9.9 GHz, accounting for a relative bandwidth of over 95.5%. The VSWR response across the bandwidth features a multiple resonance operation. Also, simulation and measurement are in good agreement.

It is noted that, SMA connector as well as RF cable has not been considered in simulation. However, in measurement, the antenna is fed by the VNA via an FR cable and an SNA connector. Even though, good agreement between simulation and measurement can be seen in Fig. 5.3.

Fig. 5.4 illustrates the measured radiation patterns at different frequencies in both E plane and H plane. As can be seen from this figure, in the low frequency region, antenna radiation pattern is similar to that of a conventional dipole whereas in the high frequency region, there are some additional beams. This may suggest that at the low frequencies, the dipole plays a significant role in antenna performance while at



Figure 5.4: Measured cross-polarization (dashed line) and co-polarization (solid line) radiation patterns of the antenna:: (a) E-plane 3.5 GHz; (b) E-plane 5.5 GHz; (c) E-plane 7.5 GHz; (d) E-plane 9.7 GHz; (e) H-plane 3.5 GHz; (f) H-plane 5.5 GHz; (g) H-plane 7.5 GHz; (h) H-plane 9.7 GHz.



Figure 5.5: Measured antenna gain [dBi] in XY plane

high frequencies; a combination of radiation components (including transmission line, dipole, and the patch) may make the antenna more directional.

The antenna also offers good gains in E plane as shown in Fig. 5.5. In the entire

its bandwidth, antenna peak gain varies from about 1.4 dBi to 5.2 dBi. The maximum gain can be achieved at frequency 6.36 GHz. This value is much better than that of a conventional half-wave dipole.

Furthermore, gain at 90-degree direction is also presented. Comparing with the peak, the gain at 90-degree direction is smaller in high frequency region. This is because at high frequency radiation patterns may be distorted due to mutual coupling of components, then the main lobe is changed into other direction.

In order to provide an insight view of antenna performance, we explore the current distributions in simulation at some different frequencies as shown in Fig. 5.6. At the low frequency region of the antenna bandwidth (around 3.5 GHz), currents on the patch and transmission line are strong. Thus, they play a role as a radiation component to extend antenna bandwidth into the lower frequency region. The main radiation part is the dipole since electric currents on it is strong compared with currents on other parts. As a result, radiation pattern is similar to that of a conventional dipole as shown in Figs. 5.4(a) and 5.4(b).

On the other hand, at high frequency region, currents on the dipole and the patch are relatively weak whereas a majority of the electric currents is concentrated on the transmission line. Thanks to the unbalanced design of transmission line as well as mutual coupling between the dipole, the patch and the transmission line, the transmission line will act as a radiation part. It would be important to note that the upper line of the transmission line consists of two segments separated by the feeding line of the dipole. These segments are corresponding to multiple resonant operations at the high frequency region.

5.2.3 Key Parameter Studies

In this section, we highlight the effects of some key parameters by successively adjusting them while keeping the others unchanged.



Freq. 9.7 GHz

Figure 5.6: Simulated current distributions

Width of substrate-Related (n): When compared with other available UWB antennas [64]-[71], one of the advantage of this proposed antenna is the small dimension of substrate width. With this distinguished feature, the antenna can be easily integrated into a narrow space in portable devices. When designing the antenna, we tried to optimize it as small as possible. In fact, this dimension has a critical effect to impedance matching of the antenna, particularly in high frequency range of antenna bandwidth. The reason is because it directly relates to mutual coupling between the dipole and the transmission line, which both are very important in antenna operation. Fig. 5.7 illustrates the effect of width of substrate on the antenna operating bandwidth. Since impedance matching of the antenna is much sensitive on mutual coupling between antenna components, the variation of width of substrate will significantly result to frequency of resonance operation. Thus, as can be seen from Fig. 5.7, when *n* equals to 8 mm or 10 mm, at some different frequencies (for example 5.7 GHz or 8.8 GHz with *n* = 8 mm), antenna becomes mismatched, and VSWR value increases. For VSWR-less-than-two bandwidth, *n* has been chosen equal to 9 mm.



Figure 5.8: Effects of varying length of dipole

Dipole arm-Related (*m*): The dipole obviously plays an important role in the whole antenna performance. Among parameters of the dipole, we examine the variation of length of dipole arm as it would be the most important. Fig. 5.8 shows the effect of varying the parameter on the impedance matching. As can be seen from the figure, the VSWR characteristic of the antenna on low frequency region has a strong



Figure 5.9: Effects of varying length of loaded patch

fluctuation with a small change in the length of dipole arm. In the meantime, at high frequency region, VSWR is almost unchanged. This highlights that, at low frequency region, the dipole is a primary radiation part.

Length of loaded patch-Related (d2): Since electric currents on the patch shown in Fig. 5.6 are not much strong, the effect of the patch on impedance matching, therefore, is not major. Fig. 5.9 shows the effect of this dimension. From this figure, we can see that resonating frequencies, where antenna performs with good matching, are almost unchanged. The patch may support much on extending antenna bandwidth into low frequency region. As can be seen, with a larger patch (d2 = 25 mm), the antenna can offer a slightly wider bandwidth. We are working to optimize the size of the patch which would be smaller in expectation.

5.3 Chapter Summary

A compact printed UWB dipole antenna was proposed in this chapter. The total volume of the antenna is only 9 mm \times 57.5 mm \times 1.6 mm with a simple design. An-

tenna measured results show that the proposed antenna offers a bandwidth of 95.5% for VSWR less than 2, covering from 3.5 GHz to 9.9 GHz. It has been highlighted that in term of impedance matching, the antenna is not much affected from RF cables. We also examined antenna radiation patterns at different frequencies. Furthermore, some parametric studies of the geometric and electric parameters of the proposed antenna were explored within detailed discussions. This antenna would be a good reference to design compact UWB-MIMO antennas.

Chapter 6

Conclusions and Future Work

This final chapter summarizes the main results of this dissertation and highlights possible areas for future research.

6.1 Conclusions

In this dissertation, we have proposed and discussed two compact MIMO antennas and its performance in practical MIMO systems in different environments. Moreover, we proposed a simple broadband antenna and its two broadband MIMO antennas for MIMO applications in cognitive radio. Experiments with the proposed MIMO antennas inside a reverberation chamber in a wide range frequency are also conducted. In addition, we have developed an UWB dipole antenna for UWB-MIMO applications. The antenna is designed within a compact size, simple form, but offers good characteristics.

At first, the designs of two novel wideband compact MIMO antennas for MIMO wireless communications are illustrated. One has three ports, whereas the other has six ports. These MIMO antennas achieved a bandwidth over 16% at the centre frequency of 2.6 GHz. Mutual couplings between ports of the antennas are very low. They are kept under -20 dB and -18 dB for the three-port and the six-port MIMO antennas

respectively. The size is only $40 \text{ mm} \times 40 \text{ mm} \times 40 \text{ mm}$ for three-port MIMO antenna and 56 mm \times 56 mm for the six-port MIMO antenna at the centre frequency of around 2.6 GHz.

We also presented the results of measurements on MIMO systems that utilized the proposed MIMO antennas in different environments. Measured data were processed in order to examine the channel characteristics such as received signal levels or CDFs of eigenvalues. Detailed explanations in data normalization or theoretical calculations of PDFs for i.i.d. Rayleigh fading environment for 3×3 or 3×6 MIMO cases were also presented. Furthermore, the effects of the compact MIMO antennas and linear array antennas on channel capacity were investigated. As a result, high capacity can be achieved from the MIMO systems which utilized the proposed compact MIMO antennas.

Successively, we proposed a simple and compact broadband antenna. Detailed explorations are conducted to analyze the performance of the antenna. The antenna offers a wide bandwidth of over 50%, extending from approximately 2.4 GHz to 4.0 GHz. It also has high gain and high cross polarization levels. In additional, we proposed two simple broadband antenna MIMO antennas that are designed based on the proposed broadband antenna. Measured results show that these MIMO antennas also have a relative bandwidth of over 50%. Mutual couplings are kept under -10 dB at low frequencies and under -20 dB at high frequencies in the bandwidth of the broadband MIMO antennas.

Some MIMO experiments were conducted inside a reverberation chamber in a wide range of frequency to examine the change of channel capacity over a wide frequency range. It has been pointed out that, in all considered MIMO configurations, the channel capacity mostly remains unchanged in the bandwidth of the MIMO antennas whereas it is reduced remarkably outside of the band. Thanks to good performances of the proposed broadband antenna as well as the broadband MIMO antennas, we suggest to utilize them in broadband applications such as MIMO systems in cognitive radio.

Finally, we proposed a compact UWB dipole antenna within a small size of 9 mm \times 57.5 mm \times 1.6 mm. Antenna characteristics such as VSWR, radiation patterns, current distributions are investigated carefully. Some key parameters are also highlighted with detailed discussions. Because of the compact size and simple design, the proposed UWB antenna can be used to develop UWB-MIMO antennas for UWB-MIMO communications.

6.2 Future Work

Here, we highlight possible areas for further research in MIMO antennas for advanced wireless communications systems.

- Since the broadband antenna is electrically not compact, we are working to reduce its size while try to enhance its bandwidth, perhaps covering UWB band.
- Since the broadband antenna is very simple, it is expected that designing a twelve-port cube-based broadband MIMO antenna will be realized soon.
- Frequency reconfigurable antennas also may be developed from the proposed broadband antenna.

Finally, we are also planning to optimize parameters of the broadband antenna using genetic algorithm.

Appendix A

Theoretical expressions for the marginal distribution of all eigenvalues of MIMO correlation matrixs in i.i.d. Rayleigh fading environment is introduced in [20]. The main point is based on the calculations for the largest eivenvalue. The marginal distribution function of the largest eigenvalue is presented as

$$P(\lambda_1 \in [0, \lambda]) = \frac{|G(\lambda)|}{\prod_{k=1}^{N_0} (N_0 - k)! (M_0 - k)!}$$
(1)

where $N_0 = \min(N_t, N_r)$, $M_0 = \max(N_t, N_r)$, $G(\lambda) \in \Re^{N_0 \times N_0}$ is a matrix, and $G_{m,n}(\lambda)$ is represented by the lower incomplete gamma function $\gamma(M_0 - N_0 + m + n - 1, \lambda)$. Then, the determinant $|G(\lambda)|$ in Eq. (1) can be computed using the following formula of the lower incomplete gamma function [73]

$$\gamma(s,x) = (s-1)! \left(1 - \sum_{k=0}^{s-1} \frac{x^k}{k!} e^{-x} \right).$$
⁽²⁾

Since the calculation for the largest eigenvalue is completed, the final calculation of density functions of eigenvalues is also explored in the combination of polynomial
and exponential functions as

$$p(\lambda_i) = \sum_{k=i}^{N_0} c^{(i)}{}_k \cdot a_k(\lambda_i) \cdot e^{-(k+1)\lambda_i}.$$
(3)

The polynomials and coefficients in this expression can be derived in a number of calculations, that may take a long time when the number of antennas in MIMO is large. The coefficients $c^{(i)}{}_{k}$ is computed according to the recurrence expression below.

$$c_k^{(i)} = (-1)^{(k-i)} \times \begin{cases} 1 & \text{if } i = 0 \text{ or } k = i \\ |c^{(i-1)}_{k-1}| + |c^{(i)}_{k-1}| & \text{otherwise} \end{cases}$$

Furthermore, the polynomial $a_k(\lambda_i)$ in Eq. (3) could be determined from identity method as following explanation. The first step is to calculate the distribution function $P(\lambda_1)$ of the largest eigenvalue presented in Eq. (1). The next is to take the differential of $P(\lambda)$ with respect to λ to get the density function $p(\lambda)$ as equation:

$$p(\lambda) = \frac{\mathrm{d}}{\mathrm{d}\lambda} P(\lambda) \tag{5}$$

The final step of this identity approach is to identify common terms with respect to exponential $e^{-k\lambda}$. It is noted that, as shown in Eq. (3), the coefficient of $e^{-k\lambda}$ will become $a_{k-1}(\lambda_i)$ after replacing λ by λ_i .

We calculated polynomials for several N_t and N_r cases that are considered in this thesis as following.

For 2×2 MIMO:

$$a_0(\lambda) = 2 - 2\lambda + \lambda^2. \tag{6}$$

$$a_1(\lambda) = -2. \tag{7}$$

For 2×4 MIMO:

$$a_0(\lambda) = 2\lambda^2 - \lambda^3 + \frac{1}{6}\lambda^4.$$
(8)

$$a_1(\lambda) = -2\lambda^2 - \lambda^3 - \frac{1}{6}\lambda^4.$$
(9)

For
$$3 \times 6$$
 MIMO

$$a_0(\lambda) = \frac{5}{2}\lambda^3 - 2\lambda^4 - \frac{5}{8}\lambda^5 - \frac{1}{12}\lambda^6 + \frac{1}{240}\lambda^7.$$
 (10)

$$a_1(\lambda) = 5\lambda^3 + \lambda^4 - \frac{1}{4}\lambda^5 - \frac{1}{12}\lambda^6 + \frac{1}{120}\lambda^7 + \frac{1}{120}\lambda^8 - \frac{1}{2880}\lambda^9 + \frac{1}{2880}\lambda^{10}.$$
 (11)

$$a_2(\lambda) = \frac{5}{2}\lambda^3 + 3\lambda^4 + \frac{13}{8}\lambda^5 + \frac{1}{2}\lambda^6 + \frac{7}{80}\lambda^7 + \frac{1}{120}\lambda^8 + \frac{1}{2880}\lambda^9.$$
 (12)

For 4×4 MIMO:

$$a_0(\lambda) = 4 - 12\lambda + 18\lambda^2 - \frac{34}{3}\lambda^3 + \frac{7}{2}\lambda^4 - \frac{1}{2}\lambda^5 + \frac{1}{36}\lambda^6.$$
 (13)

$$a_1(\lambda) = 12 - 24\lambda + 24\lambda^2 - \frac{8}{3}\lambda^3 + \frac{4}{3}\lambda^4 - \frac{4}{3}\lambda^5 + \frac{4}{9}\lambda^6 - \frac{1}{18}\lambda^7 + \frac{1}{72}\lambda^8.$$
 (14)

$$a_2(\lambda) = 12 - 12\lambda + 6\lambda^2 + \frac{14}{3}\lambda^3 + \frac{23}{6}\lambda^4 + \frac{5}{6}\lambda^5 + \frac{1}{12}\lambda^6.$$
 (15)

$$a_3(\lambda) = 4. \tag{16}$$

References

- M. A. Jensen and J. W. Wallace, "A Review of Antennas and Propagation for MIMO Wireless Communications," *IEEE Trans. Antennas Propagat.*, vol. 52, no. 11, pp. 2810-2824, Nov. 2004.
- [2] Y. Karasawa, "Innovative Antennas and Propagation Studies for MIMO Systems," *IEICE Trans. Commun.*, vol. E90-B, no. 9, pp. 2194-2202, Sep. 2007.
- [3] B. N. Getu and J. B. Andersen, "The MIMO Cube-A Compact MIMO Antenna," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 1136-1141, May 2005.
- [4] N. K. Das, T. Inoue, T. Taniguchi, and Y. Karasawa, "An Experiment on MIMO System Having Three Orthogonal Polarization Diversity Branches in Multipath-rich Enviroment," in *Proc. IEEE 60th Veh. Technol. Conf.*, vol. 2, LA, pp. 1528 - 1532, Sep. 26-29, 2004.
- [5] C. Y. Chiu, J. B. Yan, and R. D. Murch, "Compact Three-port Orthogonally Polarized MIMO Antennas," *IEEE Antennas Wireless Propagat. Lett.*, vol. 6, pp. 619-612, Dec. 2007.
- [6] J. Sarrazin, Y. Mahe, S. Avrillon, and S. Toutain, "Investigation on Cavity/slot Antennas for Diversity and MIMO Systems: The Example of a Three-port Antenna," *IEEE Antennas Wireless Propagat. Lett.*, vol. 7, pp. 414-417, 2008.

- [7] M. Shinozawa, N. K. Das, T. Taniguchi, and Y. Karasawa, "Tri-Polarization MIMO Compact Antenna and Its Performance Evaluation in Multipath-Rich Environment," *IEICE Trans. Commun.*, vol. J92-B, no. 11, pp. 262-270, Jan. 2009.
- [8] W. Ni, and N. Nakajima, "Compact and High Performance MIMO Ceramic Antenna for Portable Terminals," *J. of Electromagn. Waves and Appl.*, vol. 23, pp. 1345-1355, 2009.
- [9] D. W. Browne, M. Manteghi, M. P. Fitz, and Y. Rahmat-Samii, "Experiments with Compact Antenna Arrays for MIMO Radio Communications," *IEEE Trans. Antennas Propogat.*, vol. 54, no. 11, Dec. 2006.
- [10] K. Nishimori, Y. Makise, M. Ida, R. Kudo, and K. Tsunekawa, "Channel Capacity Measurement of 8 × 2 MIMO Transmission by Antenna Configurations in an Actual Cellular Environment," *IEEE Trans. Antennas Propagat.*, vol. 54, no. 11, pp. 3285-3291, Nov. 2006.
- [11] P. Kyritsi, D. C. Cox, R. A. Valenzuela, and P. W. Wolniansky, "Effect of Antenna Polarization on the Capacity of a Multiple Element System in an Indoor Environment," *IEEE Jour. Selected Area in Commun.*, vol. 20, no. 6, pp. 1227-1239, Aug. 2002.
- [12] C. C. Martin, J. H. Winters, and N. R. Sollenberger, "MIMO Radio Channel Measurements: Performance Comparison of Antenna Configurations," in *Proc. IEEE* 54th Veh. Technol. Conf., vol. 2, Atlantic City, NJ, USA, pp. 1225-1229, Oct. 2001.
- [13] V. Erceg, P. Soma, D. S. Baum, and S. Catreux, "Multiple-input multiple-output fixed wireless radio channel measurements and modeling using dual-polarized antennas at 2.5 GHz," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 2288-2298, Nov. 2004.

- [14] "IEEE standards definitions of terms for antenna", IEEE Transactions on Antennas and Propagation, vol. AP-17, no. 3, May. 1969 and vol. AP-22, no. 1, Jan. 1974.
- [15] C.A. Balanis, Antenna theory analysis & Design, 2nd. Edition, John Wiley & Sons, NewYork, 1997.
- [16] Federal Communications Commission, Washington, DC, "FCC report and order on ultra wideband technology", 2002.
- [17] A. J. Paulraj, D. A. Gore, R. U. Nabar, and H. Bolcskei, "An overview of MIMO communications a key to gigabit wireless," *Proceedings of the IEEE*, vol. 92, no. 2, pp. 198.218, Feb. 2004.
- [18] M. Kang and M.-S. Alouini, "Largest eigenvalue of complex Wishart matrices and performance analysis of MIMO MRC systems", *IEEE J.Sel. Areas Commun.*, vol. 21, no. 3, pp. 418-426, Apr. 2003.
- [19] G. Burel, "Statistical analysis of the smallest singular value in MIMO transmission systems," in *Proc. WSEAS. Int. Conf. on Signal, Speech and Image Processing*, Skiathos Island, Greece, Sept. 2003.
- [20] T. Taniguchi, S. Sha, and Y. Karasawa, "Analysis and Approximation of Statistical Distribution of Eigenvalues in i.i.d. MIMO Channels under Rayleigh Fading," *IEICE Trans. Fundamentals*, vol.E91-A, no. 10, pp. 2808-2817, Oct. 2008.
- [21] Y. Karasawa, "MIMO Propagation Channel Modeling," IEICE Trans. Commun., Special section on Recent Progress in Antennas and Popagation Researches, vol.E88-B, no.5, pp.1829-1842, 2005.
- [22] J. W. Wallace, M. A. Jensen, A. L. Swindlehurst, and B. D. Jeffs, "Experimental

Characterization of the MIMO Wireless Channel: Data Acquisition and Analysis," *IEEE Trans. Commun.*, vol. 2, no. 2, pp. 335-343, Mar. 2003.

- [23] B. Wang, and A. G. Burr, Effect of element radiation patterns on the capacity of MIMO system, in *Proc. IEEE Int. Symp. on Microwave, Antenna, Propagation and EMC Tech. for Wireless Comms*, vo. 2, pp. 1448–1451, 8-12 Aug. 2005.
- [24] C. Waldschmidt, T. Fugen, and W. Wiesbeck, "Spiral and dipole antennas for indoor MIMO-systems," *IEEE Antennas Wireless Propagat. Lett.*, vol. 1, no. 1, pp. 176178, 2002.
- [25] C. Y. Chiu, J. B. Yan, and R. D. Murch, "24-port and 36-port antenna cubes suitable for MIMO wireless communications," *IEEE Trans. Antennas Propagat.*, vol. 56, pp. 1170-1176, Apr. 2008.
- [26] M. A. Andrews, P. P. Mitra, and R. Carvalho, "Tripling the Capacity of Wireless Communication Using Electromagnetic Polarization," *Nature*, vol. 409, pp 316-318 Jan. 2001.
- [27] T. Svantesson, M. A. Jensen, and J. W. Wallace, "Analysis of electromagnetic field polarizations in multi-antenna systems," *IEEE Trans. Wireless Commun.*, vol. 3, pp. 641-646, Mar. 2004.
- [28] R. Janaswamy, "Effect of element mutual coupling on the capacity of fixed length linear arrays", *IEEE Antennas Wireless Propagat. Lett.*, vol. 1, no. 1, pp. 157-160, 2002.
- [29] Yang, F. and Y. Rahmat-samii, "Microstrip antennas integrated with electromagnetic band-gap (EBG) structures: A low mutual coupling design for array applications," *IEEE Transaction on Antennas and Propagation*, vol. 51, no. 10, pp. 2936-2946, 2003.

- [30] P.J. Ferrer, J.M. Gonzlez-Arbesu, and J. Romeu, "Decorrelation of two closely spaced antennas with a Metamaterial AMC Surface," *Microw. Opt. Tech. Lett.*, vol. 50, no. 5, pp. 1414-1417, May 2008.
- [31] D. Guha, S. Biswas, T. Joseph and M. T. Sebastian, "Defected ground structure to reduce mutual coupling between cylindrical dielectric resonator antennas", *Electronics Letters*, vol. 44, no. 14, pp.836–837, Jul. 2008.
- [32] S. H. Hwang, T. S. Yang, J. H. Byun, A. S. Kim, "Complement Pattern on Metamaterial Antenna for Reducing Mutual Coupling in MIMO. Systems," in *Eur. Conf. on Antennas & Prop. 2009*, Berlin, Mar. 2009.
- [33] N. Nakajima, T. Yamazaki and W. Ni, "Mutual Coupling Cancellation for Compact MIMO Antenna with 3 dB Hybrid," in *Proc. of IEEE 2nd International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology*, Chennai, India, 28th Feb 03rd Mar. 2011.
- [34] S.Chen, Y.Wang and S.Chung, "A decoupling technique for increasing the port isolation between two strongly coupled antennas", *IEEE Trans. Antennas Propagat.*, vol.56, pp.3650-3658, Dec. 2008.
- [35] S. Dossche, S. Blanch, and J. Romeu, "Three different ways to decorrelate two closely spaced monopoles for MIMO applications," in *Proc. IEEE/ACES Int. Conf.Wireless Commun. Appl. Comput. Electromagn.*, pp. 849-852, Apr. 2005.
- [36] C. G. Christodoulou, "Cognitive radio: the new frontier for antenna design?," *IEEE Antenna and Propagat. Society Website*,[Online] Available: www.ieeeaps.org/pdfs/APSwebsite-Christos.pdf, 2009.
- [37] J. Boerman and J. T. Bernhard, "Performance study of pattern reconfigurable

antennas in MIMO communication systems," *IEEE Trans. Antennas Propagat.*, vol. 56, no. 1, pp. 231-236, Jan. 2008.

- [38] D. Piazza and K.R. Dandekar, "Reconfigurable antenna solution for MIMO-OFDM systems," *Electron. Lett.*, vol. 42, p.446, 2006.
- [39] B. A. Cetiner, H. Jafarkhani, J. Y. Qian, H. J. Yoo, A. Grau, and F. De Flaviis, "Multifunctional reconfigurable MEMS integrated antennas for adaptive MIMO systems," *IEEE Commun. Mag.*, vol. 42, no. 12, pp. 6270, Dec. 2004.
- [40] B. A. Cetiner, J. Y. Qian, G. P. Li, and F. De Flaviis, "A reconfigurable spiral antenna for adaptive MIMO systems," *EURASIP J. Wireless Commun. Networking*, vol. 2005, no. 3, pp. 382389, Aug. 1, 2005.
- [41] T. Kaiser, F. Zheng, and E. Dimitrov, "An overview of ultra wideband systems with MIMO," *Proceedings of the IEEE*, vol.97, no.2, pp.285-312, Feb. 2009.
- [42] Q. Ma, B.-H. Sun, J.-F. Li, and Q.-Z. Liu, "Broadband array antenna with Marchand balun for 5.8 GHz band notched UWB application," *Microwave Opt. Technol. Lett.* vol. 51, no. 6, pp. 1537-1539, Jun. 2009
- [43] M. Jusoh, M. F. Jamlos, M. R. Kamarudin, and F. Malek, "A MIMO antenna design challenges for UWB Application," *Progress In Electromagnetics Research B*, vol. 36, pp. 357-371, 2012.
- [44] A. I. Najam, Y. Duroc, and S. Tedjini, "Design & Characterization of an Antenna System for UWB-MIMO communications Systems", in *Proc. the Fourth European Conf. on Antenna and Propagation*, Apr. 2010.
- [45] A. I. Najam, Y. Duroc, and S. Tedjni, "UWB-MIMO Antenna with Novel Stub Structure," in *Progress In Electromagnetics Research C*, vol. 19, pp. 245-257, 2011.

- [46] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Hand-book*, Artech. House, Norwood, MA,2001.
- [47] J. D. Kraus and R. J. Marhefka, *Antennas for All Applications*, 3rd Ed., McGraw-Hill, Boston, 2002.
- [48] M. Ameya, M. Yamamoto, T. Nojima, and K. Itoh, "Broadband Printed Dipole Antenna Consisting of Self-Complementary Radiating Element and Tapered Microstrip Line", in *Proc. ISAP 2005 Conf. on Antenna and Propagation*, pp. 137-140, 2005.
- [49] L.C. Lukama, D.J. Edwards and A. Wain, "Application of three-branch polarisation diversity in the indoor environment," *IEE Proc.-Commun.*, Vol. 150, No. 5, pp. 399-403, Oct. 2003.
- [50] M. Nakagami, "The *m*-Distribution A general formula for intensity distribution of rapid fading," in *Statistical Methods in RadioWave Propagation W. G. Hoffman*, Ed. Oxford, U. K. Pergamon, 1960.
- [51] Z.N Chen and M.Y.W Chia, Broadband planar antennas: design and applications, John Wiley & Sons, Ltd, Chichaster, 2006.
- [52] M. Palandoken, A. Grede and H. Henke: "Broadband microtrip antenna with lefthanded metamaterial", *IEEE Trans. Antennas Propagat.*, vol. 57, no. 2, pp. 331-338, Feb. 2009.
- [53] J. Deng: "A novel broadband antenna with right/left-handed transmission line", in *Proc. IEEE Comm., Circuits and Systems, ICCCAS 2008. Conf.*, pp. 200-202, May 2008.
- [54] K. M. Luk, C.L. Mak, Y.L. Chow, and K.F. Lee, "Broadband microstrip patch antenna", *Electronics Lett.*, vol. 34, no. 15, pp. 1442-1443, Jul. 1998.

- [55] L. Jian-Ying and T.P. Khiang: "Study of broadband printed dipole antennas", *Microwave and Optical Technol. Lett.*, vol. 52, no. 1, pp. 184-187, Jan. 2010.
- [56] S. Gao and A. Sambell: "A simple broadband printed antenna", *Progress In Electromagnetics Research*, vol. 60, pp. 119-130, 2006.
- [57] M. T. Islam, M. N. Shakib, and N. Misran, "Broadband e-h shaped microstrip patch antenna for wireless systems," *Progress In Electromagnetics Research*, vol. 98, pp. 163-173, 2009.
- [58] Y. Coulibaly, T. A. Denidni, H. Boutayeb, L. Talbi, "Design of a new broadband dielectric resonator antenna", in *Proc. EUCAP Conf.*, France, Nov. 2006.
- [59] D. Guha, "Broadband design of mirostrip antennas: recent trends and developments", *Mechanics, Autodmatic Control and Robotics*, vol.3, no 15, pp. 1083-1088, 2003.
- [60] IEEE 802.16-2001, "IEEE Standard for local and metropolitan area networks. Part 16: air interface for fixed broadband wireless access systems," Apr. 2002.
- [61] V.-H. Pham, J.-Y. Chouinard, A. Semmar, X. Wang, and Y. Wu, "On the Channel and Signal Cross Correlation of Downlink and Uplink Mobile UHF DTV Channels With Antenna Diversity," IEEE Trans. Broadcasting, vol. 56, no. 2, pp. 235-248, Jun. 2010.
- [62] J. P. Kermoal, L. Schumacher, K. I. Pedersen, P. E. Mogensen, F. Frederiksen, "A stochastic MIMO radio channel model with experimental validation," IEEE J. Sel. Areas Commun., vol. 20, no. 6, Aug. 2002.
- [63] Y. Karasawa, Radiowave Propagation Fundamentals for Digial Mobile Communications (Japanese Edition), Corona, Tokyo, 2003.

- [64] Z.N. Chen, T. S. P. See, X. Qing, "Small printed ultrawide-band antenna with reduced ground plane effect," *IEEE Trans. Antennas Propagat.*, vol .55, no.2, pp.383-388, Feb. 2007.
- [65] M. John and M. J. Ammann, "Antenna optimization with a computationally efficient multiobjective evolutionary algorithm," *IEEE Trans. Antennas Propag.*, vol. 57, no. 1, pp. 260-263, Jan. 2009.
- [66] A. Mehdipour, K. M. Aghdam, R. F. Dana, and M. R. K. Khatib, "A novel coplanar waveguide-fed slot antenna for ultrawideband applications," *IEEE Trans. Antennas Propag.*, vol. 56, no. 12, pp. 3857-3862, Dec. 2008.
- [67] Y. J. Cho, K. H. Kim, D. H. Choi, S. S. Lee, and S.-O. Park, "A Miniature UWB Planar Monopole Antenna With 5-GHz Band-Rejection Filter and the Time-Domain Characteristics," *IEEE Trans. Antennas Propagat.*, vol .54, no.5, pp.1453-1460, May 2006.
- [68] L.-X. Li, S.-S. Zhong, and M.-H. Chen, "Compact Band-Notched Ultra-Wideband Antenna Using Defected Ground Structure," *Microwave Opt. Technol. Lett.*, vol .52, pp.286-289, Feb. 2010.
- [69] M. E. Bialkowski, and A. M. Abbosh, "Design of UWB planar antenna with improved cut-off at the out-of-band frequencies," *IEEE Antennas Wireless Propag. Lett.*, vol. 7, pp. 408-410, Nov. 2008.
- [70] Z.-A. Zheng, Q.-X. Chu, and Z.-H. Tu, "Compact Band-Rejected Ultrawideband Slot Antennas Inserting With *lambda*/2 and *lambda*/4 Resonators," *IEEE Trans. Antennas Propagat.*, vol .59, no.2, pp.390-397, Feb. 2011.
- [71] W. T. Li, X. W. Shi, and Y. Q. Hei, "Novel Planar UWB Monopole Antenna With Triple Band-Notched Characteristics," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 1094-1098, 2009.

- [72] D. T. Le, and Y. Karasawa, "A Simple Broadband Antenna for MIMO Applications in Cognitive Radio," in *Proc. IEEE Antennas Propag. Symp.*, Washington, Jul. 2011.
- [73] E. Kreyszig, Advanced Engineering Mathematics, 8th ed., Wiley, New York, 1999.

Papers related to the thesis

- Dinh Thanh Le, Masahiro Shinozawa, Yoshio Karasawa, "Wideband MIMO Compact Antennas with Tri-Polarizations", *IEICE Trans. Commun.*, vol. E94-B, no. 07, pp. 1982-1993, Jul. 2011 (Related to the chapter 3).
- [2] Dinh Thanh Le, and Yoshio Karasawa, "A Simple Broadband Antenna for MIMO Applications in Cognitive Radio", *IEICE Trans. Commun.(Special Section on Recent Progress in Antennas and Propagation in Conjunction with Main Topics of ISAP2010*), vol.E95-B, no.01, pp.18-26, Jan. 2012 (Related to the chapter 4).
- [3] Dinh Thanh Le, and Yoshio Karasawa, "A Compact Printed Ultra-Wideband Dipole Antenna Integrated with Transmission Line and Loaded Patch", In *Proc.* of 2011 TriSAI Conference, 25th-26th Aug. Daejeon, Korea (Related to the chapter 5).

Publishcations

• JOURNAL PAPERS

- Dinh Thanh Le, Masahiro Shinozawa, Yoshio Karasawa, "Wideband MIMO Compact Antennas with Tri-Polarizations", *IEICE Trans. Commun.*, vol. E94-B, no. 07, pp. 1982-1993, Jul. 2011.
- Dinh Thanh Le, and Yoshio Karasawa, "A Simple Broadband Antenna for MIMO Applications in Cognitive Radio", *IEICE Trans. Commun.(Special Section on Recent Progress in Antennas and Propagation in Conjunction with Main Topics of ISAP2010)*, vol.E95-B, no.01, pp.18-26, Jan. 2012.

• INTERNALTIONAL CONFERENCE PAPERS

- Dinh Thanh Le, and Yoshio Karasawa, "Design a Broadband Reconfigurable Antenna for Cognitive Radio", *The 2012 IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting* (to be presented).
- Dinh Thanh Le, and Yoshio Karasawa, "A Novel Compact Ultra-Wideband Dipole Antenna", *The 6th European Conference on Antennas and Propagation - EUCAP 2012*, Prague, Czech Republic, 2012 (to be presented).
- 3. Dinh Thanh Le, and Yoshio Karasawa, "A Compact Printed Ultra-

Wideband Dipole Antenna Integrated with Transmission Line and Loaded Patch", In *Proc. of 2011 TriSAI Conference*, 25th-26th Aug. Daejeon, Korea.

- Dinh Thanh Le, and Yoshio Karasawa, "A Simple Broadband Antenna for MIMO Applications in Cognitive Radio", In *Proc. of IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting*, Spokane, Washington, USA, 3rd-8th July, 2011 (Student paper competition honorable mention).
- Dinh Thanh Le, and Yoshio Karasawa, "A Novel Compact Antenna for Broadband MIMO", In Proc. of IEEE 2nd International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology, Chennai, India, 28th Feb 03rd Mar. 2011
- Dinh Thanh Le, Masahiro Shinozawa, Yoshio Karasawa, "Novel Compact Antennas for MIMO Wireless Communication Systems", In *Proc.* of *IEEE Conference on Advanced Technologies for Communications* ATC, Ho Chi Minh City, Vietnam, pp. 341 345, 20-22 Oct., 2010.

DOMESTIC CONFERENCE PAPERS

- Dinh Thanh Le, and Yoshio Karasawa, "A Simple Broadband Antenna for MIMO Applications in Cognitive Radio", Presentation slides in the 1st Inter-University Workshop on Electronics and Communications, Hanoi, Vietnam, Oct. 2011
- Dinh Thanh Le, and Yoshio Karasawa, "A Simple Broadband Antenna", *Technical report of IEICE*, AP2010-124, Vol. 110, No. 347, pp. 37-41, Dec. 2010.
- 3. Dinh Thanh Le, and Yoshio Karasawa, "A Simple Broadband Antenna",

In Proc. of IEICE Society Conference, B-1-177, p 177, Osaka, Sept. 2010.

4. Dinh Thanh Le, Masahiro Shinozawa, Yoshio Karasawa, "Novel Compact Antennas for MIMO Wireless Communication Systems", *Technical report of IEICE*, AP2010-37, Vol. 110, No. 75, pp. 31-36, Jun. 2010.

Author bibliography

Dinh Thanh LE was born in 1982 in Thanh Hoa, Viet Nam. He received B.S. and M.S. in Electronic Engineering from Le Quy Don Technical University (LQDTU), Ha Noi, Viet Nam, in 2006 and 2008, respectively. He is currently working toward a Ph.D. degree in The University of Electro-Communications (UEC), Tokyo, Japan.

From 2006 to 2008, he worked as a teaching assistant of LQDTU. Since 2009, he has been a student of Advanced Wireless Communication research Center (AWCC) in UEC. His research interests include Multi-Input Multi-Output (MIMO) antenna, broadband antenna, Ultra Wideband (UWB) antennas, reconfigurable antennas, electromagnetic band gap (EBG) structures, and microwave antennas based on EBG.

Mr. Le received "Honorable Mention" in Student Paper Competition from the 2011 IEEE AP-S Symposium and USNC/URSI Meeting. He is a student member of the Institute of Electronics, Information and Communication Engineers (IEICE), Japan.