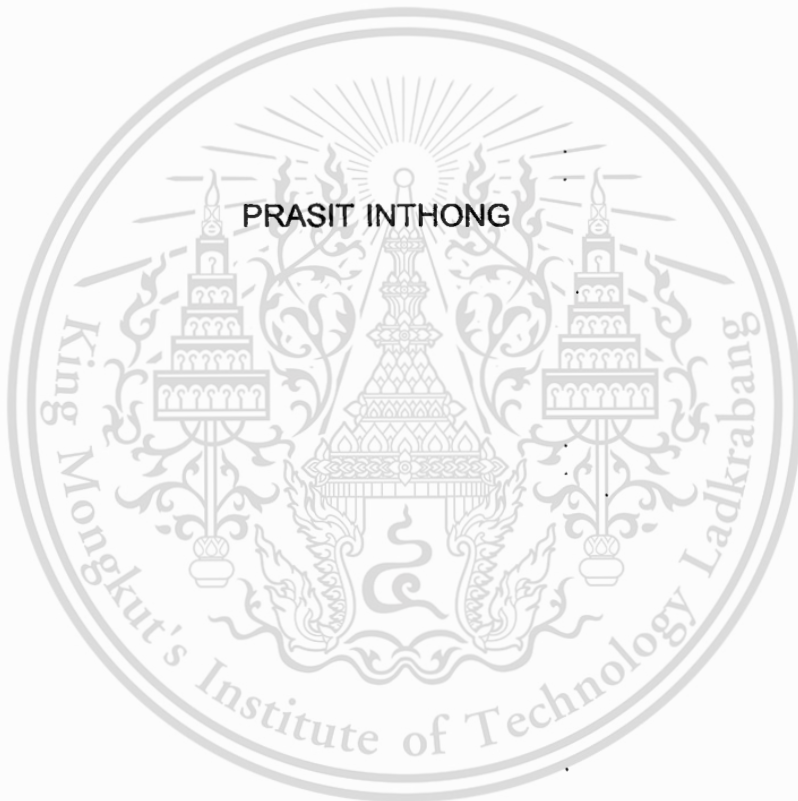


PERFORMANCE STUDY OF SWITCHED-BEAM ANTENNAS FOR  
MIMO INDOOR WIRELESS CHANNELS

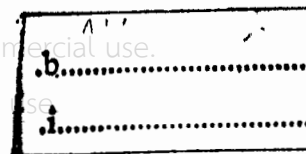


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หัวข้อวิทยานิพนธ์	การศึกษาสมรรถนะของสายอากาศสวิตซ์ลำคลื่นสำหรับช่องสัญญาณไร้สายภายในอาคารแบบหลายอินพุตหลายเอาต์พุต
นักศึกษา	นายประสิทธิ์ อินทร์ทอง
รหัสประจำตัว	44061715
ปริญญา	วิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชา	วิศวกรรมโทรคมนาคม
พ.ศ.	2547
อาจารย์ผู้ควบคุมวิทยานิพนธ์	ศ.ดร.โมไนย ไกรฤกษ์

### บทคัดย่อ

วิทยานิพนธ์ฉบับนี้เป็นการศึกษาสมรรถนะของสายอากาศสวิตซ์ลำคลื่น สำหรับช่องสัญญาณไร้สายภายในอาคารแบบหลายอินพุตหลายเอาต์พุต การศึกษาเริ่มต้นจากการจำลองแบบสายอากาศสวิตซ์ลำคลื่นอันประกอบไปด้วยสายอากาศสวิตซ์ลำคลื่นแพชเดียวกัน สายอากาศแถวลำดับแบบปรับเฟสลักษณะแบนกะทัดรัดแบบ 4 ลำคลื่น และสายอากาศแถวลำดับแบบปรับเฟสที่มีองค์ประกอบแบบสวิตซ์ลำคลื่น บนช่องสัญญาณไร้สายภายในอาคารแบบหลายอินพุตหลายเอาต์พุต เปรียบเทียบกับสายอากาศแถวลำดับทั่วไป (โมโนโพล) โดยอาศัยแบบจำลองการกระจายกระจ่าย 1 วงแหวน และ 2 วงแหวน และทำการทดสอบสายอากาศทั้งหมดบนช่องสัญญาณไร้สายภายในอาคารที่ห้องวิจัยการสื่อสารไร้สาย สำนักวิจัยการสื่อสารและเทคโนโลยีสารสนเทศ โดยการวัดหาคณลักษณะของช่องสัญญาณไร้สายภายในอาคาร แบบหลายอินพุตหลายเอาต์พุต ผลที่จากการศึกษาโดยการจำลองแบบและการทดสอบโดยการวัด นำมาเปรียบเทียบและแสดงผลในรูปแบบของสหสัมพันธ์และความจุของช่องสัญญาณ จากผลดังกล่าวยืนยันได้เป็นอย่างดีว่าสายอากาศแบบสวิตซ์ลำคลื่นสามารถที่จะนำมาใช้แทนที่สายอากาศแบบแถวลำดับทั่วไป บนช่องสัญญาณไร้สายภายในอาคารแบบหลายอินพุตหลายเอาต์พุตได้ โดยมีจุดเด่นที่ขนาดเล็ก กะทัดรัดและต้องการจำนวนเครื่องรับส่งน้อยกว่าสายอากาศแถวลำดับทั่วไป

Thesis Title	Performance Study of Switched-Beam Antennas for MIMO Indoor Wireless Channels
Student	Mr.Prasit Inthong
Student ID.	44061715
Degree	Master of Engineering
Programme	Telecommunications Engineering
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Thesis Advisor	Prof.Dr.Monai Krairiksh

## ABSTRACT

This thesis presents the performance study of switched beam antennas for MIMO indoor wireless channels. The simulation of switched beam antennas, which included a switched beam single patch antenna, a flat four-beam compact phased array antenna and a flat compact phased array of switched beam elements, on MIMO indoor wireless channels is studied and compared with conventional array antennas (monopole). The simulation is based on one-ring and two-ring scattering model, and the experiment is performed to measure the characteristics of MIMO indoor wireless channels at Wireless Communication Laboratory, Research Center for Communication and Information Technology (ReCCIT). The simulation and experimental results were compared and demonstrated in the form of correlations and channel capacities. From the results, it can be confirmed that the switched beam antenna can be used and replaced the conventional array antennas for MIMO indoor wireless channels with the advantage on small size and less transceiver required than conventional array antennas.

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# CHAPTER 1

## INTRODUCTION

### 1.1 Background of Wireless Communication System

The history of wireless communication began around 1897 when Guglielmo Marconi first established a radio link to provide continuous contact with ships sailing the English Channel [1]. Marconi had bridged the 3,000 km distance between St. John's Newfoundland in Canada and Cornwall on the southwest tip of England using Morse transmission of the letter "S" [2]. Wireless communications were becoming a practical reality. Since then, the use of wireless systems increased rapidly in 1930s to 1960s, when the number of users largely exceeded the small number of channels available. In 1970's, Bell Laboratories proposes a new concept of radio technology called the cellular concept, the concept of splitting a coverage zone into small cells, each of which reuses portions of the spectrum to increase the user capacity. After that, wireless cellular communications has been one of the fastest growing fields of wireless communication technology.

The first-generation (1G) mobile communication systems such as AMPS, TACS and MNT using analog transmission for speech services were introduced in the early 1980's [3]. Second-generation (2G) systems, which use digital transmission, were introduced in the late 1980s. Global System for Mobile Communications (GSM), Personal Digital cellular (PDC), IS-136 and IS-95 are second generation systems. The services offered by these systems cover speech and low bit rate data. The second-generation systems further evolve toward third generation (3G) systems to offer more advanced services such as medium bit rate (up to 100 kb/s) circuit and packet-switched data, such as General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE). These evolved systems are referred to as 2.5G. Nowadays, the third-generation systems should be able to offer at least 144 kb/s for high mobility users with wide coverage area and 2 Mb/s for low mobility users with local coverage [4]. The 3G evolution for Code Division Multiple Access (CDMA) systems leads to CDMA 2000. Several variants of CDMA 2000 are currently being developed, but they are based on

the fundamentals of IS-95 and IS-95B technologies. The 3G evolution for GSM, IS-136 and PDC systems are leading to Wideband CDMA (W-CDMA), also called Universal Mobile Telecommunications Service (UMTS).

Nowadays, multiple antenna systems have been proposed as an effective way to address the user demand for high data rate wireless applications. This is especially important in wireless systems that are power and bandwidth limited. Multiple-input multiple-output (MIMO) systems, can potentially achieve very high capacities [5, 6]. Several techniques that involve advanced signal processing at the transmitter and/or the receiver have been proposed [7], high data rate nearing 1 Gb/s can be achieved.

## 1.2 Purpose and Scope of the Study

This thesis presents the study results of switched-beam antennas for MIMO indoor wireless channels. In MIMO wireless communication systems, usually use dipole antenna, monopole antenna or patch antenna at both the transmitting and the receiving antennas. The MIMO systems with multiple antennas require multiple radio transceivers, it is expensive to use in practical systems. However, this drawback may be relived by using switched-beam antenna, because the switched-beam antenna requires only one radio transceiver. In this thesis, switched-beam antennas are used to simulate in an indoor environment based on the physical radio channel modeling. After that, the measurement campaign was conducted in laboratory to verify the concept that the switched-beam antennas can be used in the MIMO wireless systems.

## 1.3 Thesis Outline

The rest of this thesis is organized as follows:

Chapter 2 presents the theoretical background on the efficiency of the MIMO system compared to the single-input single-output (SISO) system. Definitions of array gain, diversity gain, channel capacity and correlation coefficient are presented.

Chapter 3 presents the structure of switched-beam antennas which are developed at the Wireless Communication Laboratory, Research Center for Communications and Information Technology (ReCCIT). The performances of the switched-beam antennas are introduced.

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Chapter 4 describes the detail of two MIMO wireless channel models and then evaluates the channel capacity of the MIMO wireless channel using the modified channel model with various switched-beam antenna configurations.

Chapter 5 describes the measurement campaign that was conducted in order to compare the theoretical results with actual channel measurements. The results of the measurement campaign in the laboratory environment with four-element of monopole antennas and three types of switched-beam antennas are presented.

Chapter 6 includes the conclusions of this thesis and suggests for future research.



# CHAPTER 2

## GENERAL BACKGROUND INFORMATION

### 2.1 Introduction

The purpose of this chapter is to provide a basic understanding of the multiple input multiple-output (MIMO) communication system, necessary for the reading of the thesis, with a special emphasis on antenna array and digital signal processing. At first, a general description of the wireless multi-element antenna channels is given. The concept of spatial diversity at both transmitting and receiving sides are then introduced by using multiple antennas, followed by a general MIMO structure and the MIMO propagation scenarios. The array and diversity gains are also discussed in the context of MIMO system. The major interesting in the MIMO system is the capacity and correlation aspect, when we compared with capacity offered by conventional single-input single-output (SISO) system.

### 2.2 Multi-Element Antenna Wireless Systems

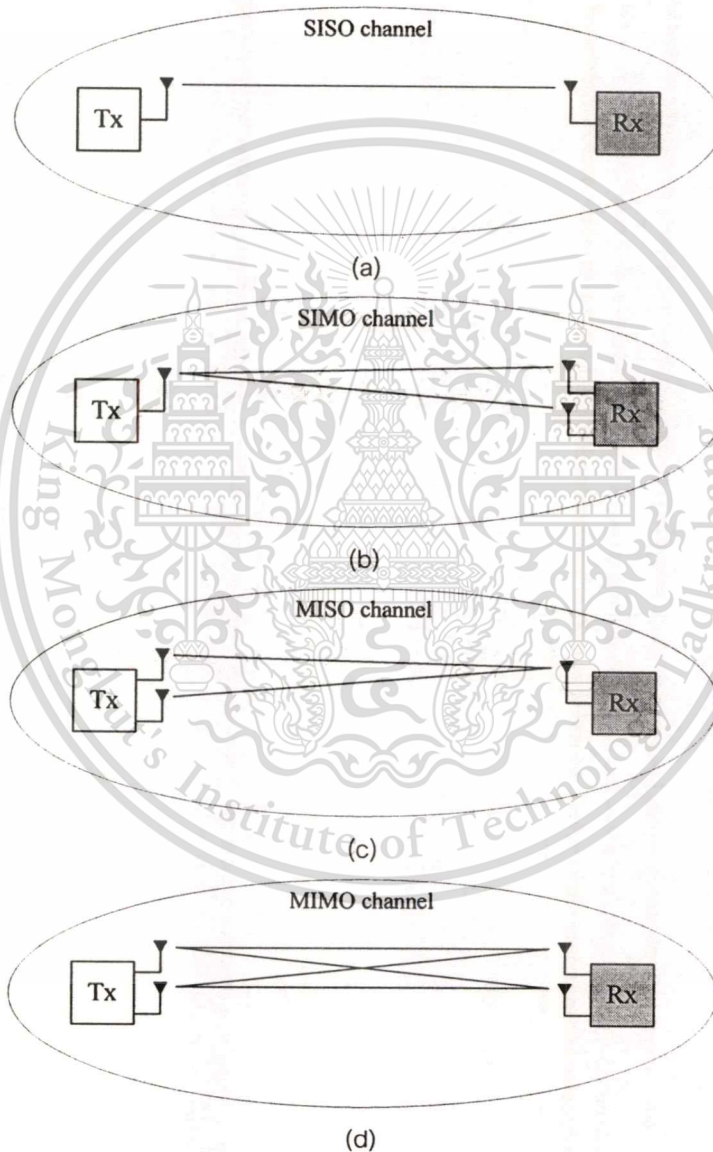
Nowadays, the demand for high data rate wireless services, such as broadband wireless access systems, wireless local area network (WLAN), third-generation networks and beyond are increasing. Internet and multimedia services have been rapidly increasing in worldwide. The radio spectrum available for wireless applications is limited. Therefore, the design of future wireless communication systems with highly spectrum efficiency is required.

Conventional wireless communication systems require single transmitting and single receiving antenna, also known as single-input single-output (SISO) system. Increasing the data rate can be achieved either by increasing the transmission bandwidth or the transmission power. However, some radio spectrum reserved for another application, such as scientific and medical applications, increasing the transmission bandwidth is impossible. Increasing the transmission power is also an undesirable way, because it will require an expensive radio amplifier. To increase the system capacity with limited bandwidth, the wireless multi-element antenna system has

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been proposed in [8]. Multiple antenna systems can be divided into three groups, the use of antenna array only at receiver, known as single-input multiple-output (SIMO) systems, the use of antenna array only at transmitter, known as multiple-input single-output (MISO) systems, and the use of antenna arrays at both transmitter and receiver, known as multiple-input multiple-output (MIMO) systems. Figure 2.1 shows classification of wireless systems as mentioned above.



**Figure 2.1** Classification of wireless systems: (a) single-input single-output (SISO), (b) single-input multiple-output (SIMO), (c) multiple-input single-output (MISO) and (d) multiple-input multiple-output (MIMO).

The MIMO communication systems use multiple antennas at both the transmitter and the receiver. Under rich multipath environments with independent multipath fading between each transmitting and receiving antenna pair, MIMO wireless communication systems achieve significant capacity gains over conventional single antenna systems [5, 6]. In principle, the information theoretic capacity of these systems can increase linearly with the numbers of antennas. In order to achieve those capacities, layered space-time architectures [9], spatio-temporal coding techniques [10] and space-time codes [11], have been proposed.

### 2.3 General MIMO Structure

MIMO systems are an extension of smart antenna systems. Traditional smart antenna systems employ multiple antennas at the receiver, whereas in a general MIMO system multiple antennas are employed both at the transmitter and the receiver. For single user communication the transmitter is defined by  $n_T$  antennas and the receiver is defined by  $n_R$  antennas, as shown in Figure 2.2.

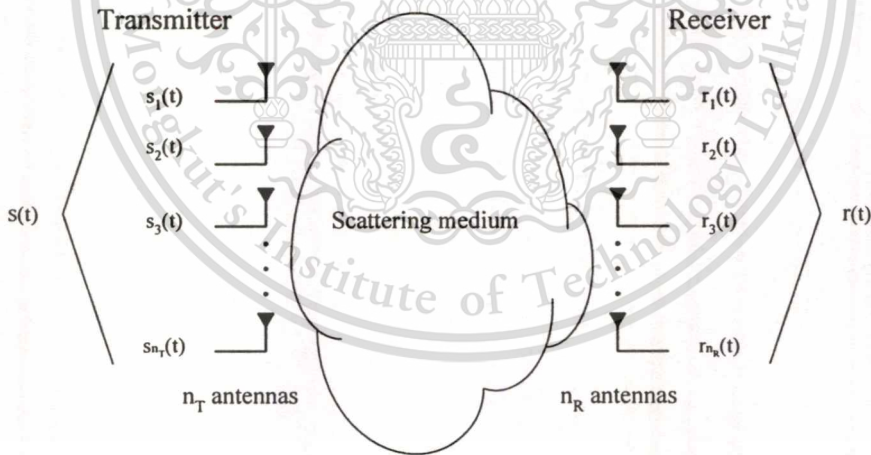


Figure 2.2 Schematic representation of a MIMO wireless system.

The input-output relationship of the received signal at the receiver can be written as

$$r(t) = H(t) * s(t) + n(t) \quad (2.1)$$

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where  $H(t)$  is the channel impulse response matrix,  $s(t)$  is the transmitted signal,  $r(t)$  is the received signal,  $n(t)$  is additive white Gaussian noise (AWGN) and  $*$  denotes convolution. If the signal bandwidth is sufficiently narrow, the channel can be treated as approximately constant over frequency (frequency flat channel). The corresponding input-output relationship simplifies to

$$r = Hs + n \quad (2.2)$$

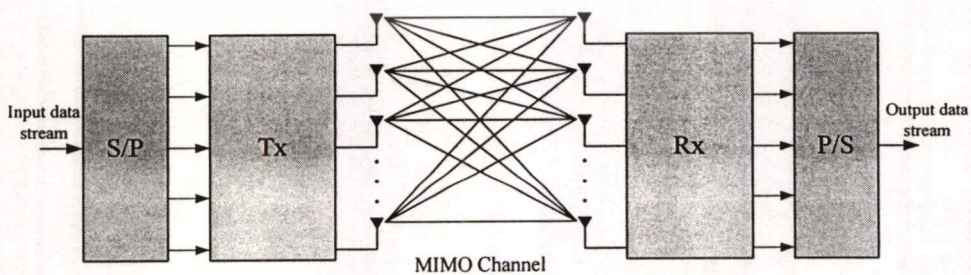
where  $r = [r_1 \ r_2 \ \dots \ r_{n_R}]^T$  is the  $n_R \times 1$  receive signal vector,

$H = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1n_T} \\ h_{21} & h_{22} & \dots & h_{2n_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{n_R1} & h_{n_R2} & \dots & h_{n_Rn_T} \end{bmatrix}$  is the  $n_R \times n_T$  channel transfer matrix,

$s = [s_1 \ s_2 \ \dots \ s_{n_T}]^T$  is the  $n_T \times 1$  transmit signal vector and  $n = [n_1 \ n_2 \ \dots \ n_{n_R}]^T$

is the  $n_R \times 1$  noise vector. The elements of channel transfer matrix  $H$  are independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian with zero mean and unit variance.

The MIMO architectures can be divided into two schemes, a spatial multiplexing and a space-time diversity coding [7]. In a spatial multiplexing system [6, 12], the transmitted data stream is demultiplexed into  $n_T$  lower data rate streams and then simultaneously sent from the  $n_T$  transmitting antennas after coding and modulating. Note that these streams occupy the same frequency bandwidth. At the receiver, each receiving antenna observes a superposition of the transmitted signal. The receiver separates each data streams and remultiplexes them to recover the original data stream. Figure 2.3 shows the schematic of spatial multiplexing system.



**Figure 2.3** Schematic of spatial multiplexing system. S/P and P/S are serial to-parallel and parallel-to-serial conversion, respectively.

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In a space-time diversity coding as shown in Figure 2.4, a number of code symbols equal to the number of transmitting antennas are generated and transmitted simultaneously, one symbol from each antenna. These symbols are generated by space-time encoder. At the receiver, by using appropriate signal processing and decoding procedure, the original information can be achieved.

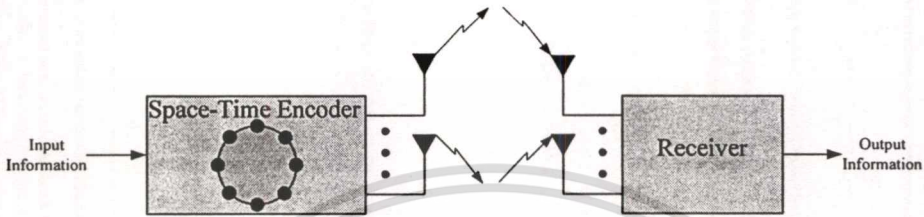


Figure 2.4 Schematic of space-time diversity coding.

## 2.4 The MIMO Propagation Scenarios

The propagation scenarios for a MIMO wireless communication system can be classified into three categories [13], as illustrated in Figure 2.5.

### 2.4.1 Uncorrelated

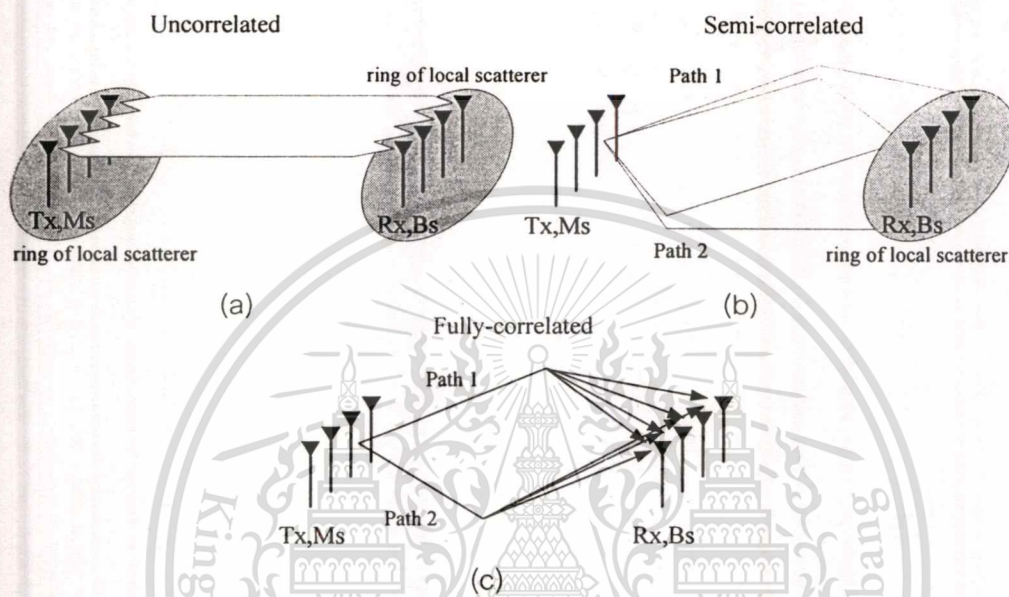
If both the transmitter and the receiver are located in a rich scattering environment (see Figure 2.5 (a)). The angular spread is high at the transmitter and the receiver. Since the distance between the transmitter and the receiver is small, the results in fading which is uncorrelated for each transmitting and receiving antenna. Therefore, a high transmit and receive diversity can be obtained.

### 2.4.2 Semi-Correlated

If only the receiver is operating in scattering environment (see Figure 2.5 (b)). The transmitter is operating without any scatterer. All channel coefficients for each transmitting antenna seen from one receiving antenna are correlated. The correlation of the channel coefficients at each receiving antenna for one transmitting antenna is very low. Therefore, a high receive diversity can be obtained.

### 4.2.3 Correlated

If low scattering environment between the transmitter and the receiver (see Figure 2.5 (c)). This is a typical line of sight (LOS) scenario which has a high correlation among the different transmitting antennas and receiving antennas. There is only small transmit and receive diversity.



**Figure 2.5** Fading correlations in MIMO wireless communication systems:

(a) uncorrelated, (b) semi-correlated and (c) correlated.

## 2.5 Array and Diversity Gain Aspect

### 2.5.1 Array Gain

Array gain in MIMO system can be received by processing at the transmitter and the receiver, resulting in an increase in average received signal-to-noise ratio (SNR). Transmit or receive array gain requires channel knowledge in the transmitter and receiver, respectively, and it depends on the number of transmitting and receiving antennas ( $n_T$  and  $n_R$ ). The channel knowledge in the receiver is typically available whereas the channel state information in the transmitter is in general more difficult to maintain.

## 2.5.2 Diversity Gain

Signal power in a wireless channel fluctuates randomly due to multipath fading. Spatial diversity techniques rely on transmitting the signal over multiple independently fading paths to the receiver. The receiver can combine the arriving signals such that the resultant signal reduces amplitude variability in comparison to a SISO system.

## 2.6 The Capacity and Correlation Aspect

### 2.6.1 Channel Capacity

The Shannon capacity formula for the SISO wireless channel is expressed as

$$C = \log_2(1 + \xi) \quad \text{bps/Hz} \quad (2.3)$$

where  $\xi$  is the signal-to-noise ratio (SNR). It is clear from the formula that increasing the SNR, the channel capacity only increases following a logarithmic law (that is 1 more bit for a 3 dB increase of SNR), but in practical systems the transmit power is limited, so that the channel capacity can not be increased with unlimited.

For the MIMO system the channel capacity expression in [6] is

$$C = \log_2 \left[ \det \left( I_{n_r} + \frac{\xi}{n_T} \cdot HH^H \right) \right] \quad \text{bps/Hz} \quad (2.4)$$

where  $I$  is the identity matrix,  $H$  is the channel transfer matrix,  $\cdot^H$  denotes complex conjugate or Hermitian transpose and  $\frac{\xi}{n_T}$  is average SNR at the transmitting antenna.

The capacity for the MIMO system can be increased by increasing both the number of antenna and average SNR. When the transmit power is limited, the channel capacity can be increased by increasing number of the transmitting ( $n_T$ ) and receiving antenna ( $n_R$ ). This is an advantage of the MIMO system over the SISO system.

In the ideal MIMO channel, no correlation exists among the several SISO channels presenting between the transmitting and the receiving sides, that is the correlation matrix of  $H$  is diagonal and the MIMO channel is decoupled into a set of parallel SISO channels. Otherwise, if some correlation exists, an interference factor has to be added, that is some entries outside the main diagonal could not be null. It is important to stress that unknown knowledge of the channel matrix at both sides of the link will be assumed in this thesis.

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### 2.6.2 Correlation

Correlation is a statistical quantity often used to compare two propagation channels. For the purposes of spatial diversity, propagation channels are defined by the locations of their transmitter and receiver antenna elements. Identical signals passing through two propagation channels may acquire different values of amplitude or phase, depending on the gain of each channel. Correlation can describe the similarity between the two channel gains and the similarity between the amplitude and phase characteristics of the two received signals. This section discusses the correlation of fading between two propagation channels and its application to spatial diversity [15].

The correlation coefficient is a normalized value of cross correlation. It has a range from zero to positive one, where a positive one indicates that the two observations are always equal, and a correlation coefficient of zero signifies the uncorrelated case. For the remainder of this thesis, the correlation coefficient is given by

$$\rho = \langle a, b \rangle = \frac{E[ab^*] - E[a]E[b^*]}{\sqrt{(E[|a|^2] - |E[a]|^2)(E[|b|^2] - |E[b]|^2)}} \quad (2.5)$$

where  $\cdot^*$ ,  $\langle \cdot, \cdot \rangle$ , and  $E[\cdot]$  are the complex conjugate, the correlation coefficient and the expectation operations.

The spatial power correlation coefficient of the MIMO channels [16] can be expressed as

$$\rho_{\substack{n_{R1}n_{T1} \\ n_{R2}n_{T2}}} = \langle |h_{n_{R1}n_{T1}}|^2, |h_{n_{R2}n_{T2}}|^2 \rangle \quad (2.6)$$

where  $h$  is the channel gain.

## 2.7 Summary

This chapter presents the necessary background to understand the principle of the MIMO wireless communication system. A general description of the MIMO structure, i.e.  $n_T$  antenna elements at the transmitter and  $n_R$  antenna elements at the receiver, is given. The major motivating factor in the MIMO wireless communication is the high spectral efficiency compared to the conventional SISO wireless communication. The theoretical capacity performance of the MIMO communication is defined from the generalized Shannon equation. An expression for the spatial power correlation

coefficient has been presented, which quantifies the similarity between two fading channels.



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# CHAPTER 3

## SWITCHED-BEAM ANTENNAS

### 3.1 Introduction

This chapter presents various types of switched-beam antennas, which are developed at the Wireless Communication Laboratory, Research Center for Communications and Information Technology (ReCCIT), King Mongkut's Institute of Technology Ladkrabang (KMITL). Switched-beam antenna is one category of smart antennas, usually is designed for mobile or wireless applications to reduce multipath propagation, suppress interference from co-channel and improve link capacity. The purpose of this chapter is to provide a basic understanding of the switched-beam antenna. At first, a general description of switched-beam antennas is given, following by the performance improvement by using the switched-beam antenna.

### 3.2 Switched-Beam Antennas

#### 3.2.1 Switched-Beam Single Patch Antenna

The switched-beam single path antenna structure [17] based on a center-fed square patch printed antenna and PIN diodes, used as RF switches to switch beam of the antenna, is proposed. The antenna configuration is shown in Figure 3.1. Usually, a patch antenna has omnidirectional pattern, however, by utilizing the PIN diodes as RF switches, the radiation in direction that the PIN diodes are shorted will be suppressed, so the directional pattern can be provided in direction that PIN diodes are not shorted. Consequently, the switched-beam single patch antenna can be accomplished by applying reverse-bias or forward-bias the PIN diodes, giving two radiation patterns switched toward x or y directions, respectively (see Figure 3.2). Maximum gain of 6.2 dBi is achieved. Low envelope correlation of 0.06 is obtained [17], demonstrating that it is feasible to apply the antenna as a diversity receiving antenna to improve received signal in wireless communication system. Prototype of switched-beam single patch antenna is illustrated in Figure 3.3. It is designed to apply for base station diversity antenna at the center frequency of 1.95 GHz.

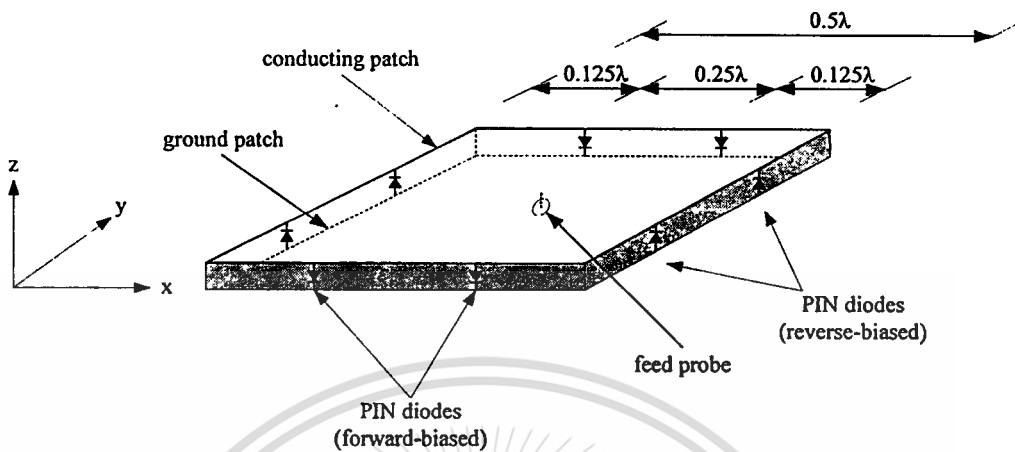


Figure 3.1 Configuration of switched-beam single patch antenna.

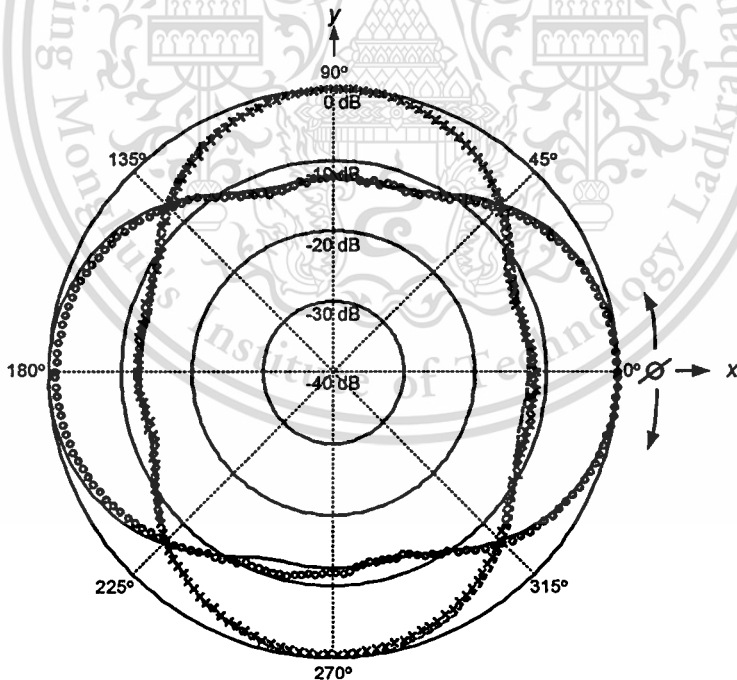
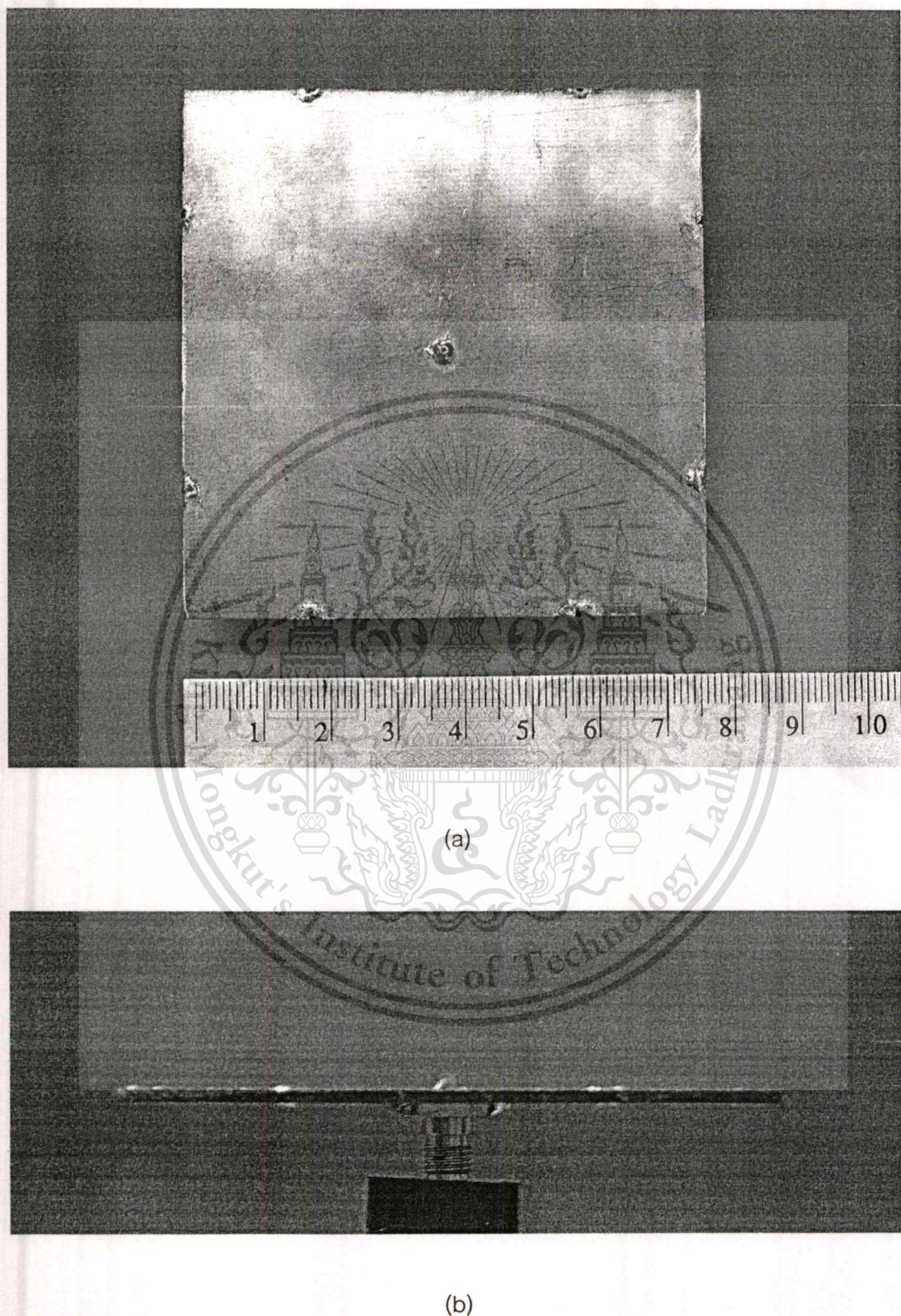


Figure 3.2 Radiation patterns of switched-beam single patch antenna, the solid line shows calculation pattern, dot and cross line show experimental patterns.



**Figure 3.3** Prototype of a switched-beam single patch antenna: (a) top view, (b) side view.

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### 3.2.2 Flat Four-Beam Compact Phased Array Antenna

A flat four-beam compact phased array antenna, as shown in Figure 3.4, is designed based on a circular array principle to achieve four switched-beams [18]. Four circular microstrip patch antennas having omnidirectional pattern are used to form a circular array for simple, low profile and compact phased array antenna structure. In addition, the main beam directions of the four-beam phased array antenna are specified to be between array elements ( $\phi = 45^\circ, 135^\circ, 225^\circ$  and  $315^\circ$ ) instead of the same as directions of array elements ( $\phi = 0^\circ, 90^\circ, 180^\circ$  and  $270^\circ$ ) that the 1-bit phase shifters with differential phase of  $80^\circ (\pm 40^\circ)$  are employed (see Table 3.1). With the array radius  $a$  of  $0.375\lambda$  at the center frequency of 1.95 GHz, the radiation patterns in four directions of  $45^\circ, 135^\circ, 225^\circ$  and  $315^\circ$  can be shown in Figure 3.5. The main beam of the antenna can be switched in four directions with the gain of about 4 dBi in each main beam direction. The diversity performance of this antenna can be provided with the envelope correlation coefficient of about 0.6. Prototype of flat four-beam compact phased array antenna is illustrated in Figure 3.6. It is divided into two parts (two layers), the antenna part (top layer) and the feed structure and phase shifter part (bottom layer).

Table 3.1 Values of phase shift for the four-beam directions.

Beam direction	Phase			
	$45^\circ$	$-40^\circ$	$40^\circ$	$40^\circ$
$135^\circ$	$-40^\circ$	$-40^\circ$	$40^\circ$	$40^\circ$
$225^\circ$	$40^\circ$	$-40^\circ$	$-40^\circ$	$40^\circ$
$315^\circ$	$40^\circ$	$40^\circ$	$-40^\circ$	$-40^\circ$

### 3.2.3 Phased Array Antenna of Switched-Beam Elements

A phased array antenna of switched-beam elements is proposed to be able to switch not only the main beam, but also the null directions [19]. Based on the flat four-beam phased array antenna as described above, four omnidirectional elements are replaced by switched-beam elements, so that not only the main beam of the antenna can be switched using 1-bit phase shifters, but the null pattern can be adapted using switched-beam elements as array elements. The switched-beam elements are the

switched-beam single patch antenna as presented in Sec.3.2.1, and the configuration of a phased array antenna of switched-beam elements is illustrated in Figure 3.7. Four switched-beam elements are arranged as a circular array with array radius of 0.5, at the center frequency of 1.95 GHz.

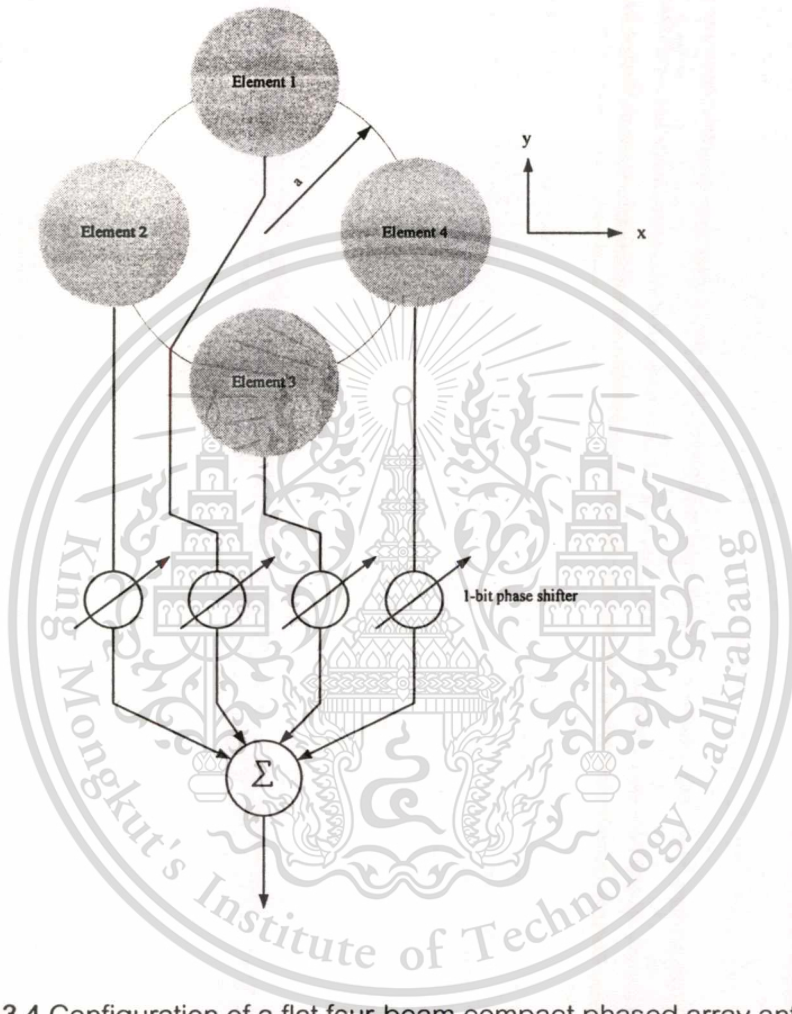


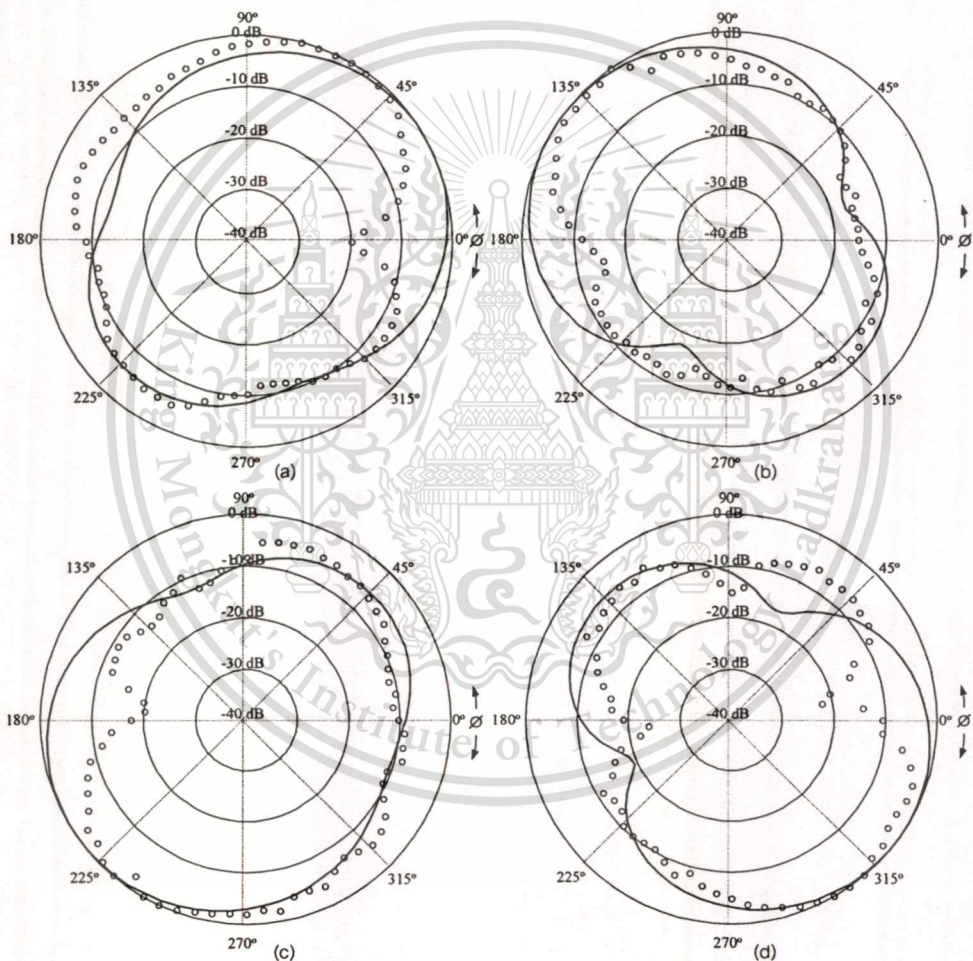
Figure 3.4 Configuration of a flat four-beam compact phased array antenna.

Since the switched-beam elements are used as the array elements instead of omnidirectional elements, the radiation patterns of the phased array antenna will not be restricted to be only four radiation patterns. By using the switched-beam single patch antenna as the array element, each element can switch beam between two directions of  $x$  and  $y$  directions, so four elements can provide  $2^4 = 16$  formats of switched-beam element pattern, resulting in 16 different null patterns in one main beam direction. Thus, it can be implied that there are 16 radiation patterns in each main beam direction, and

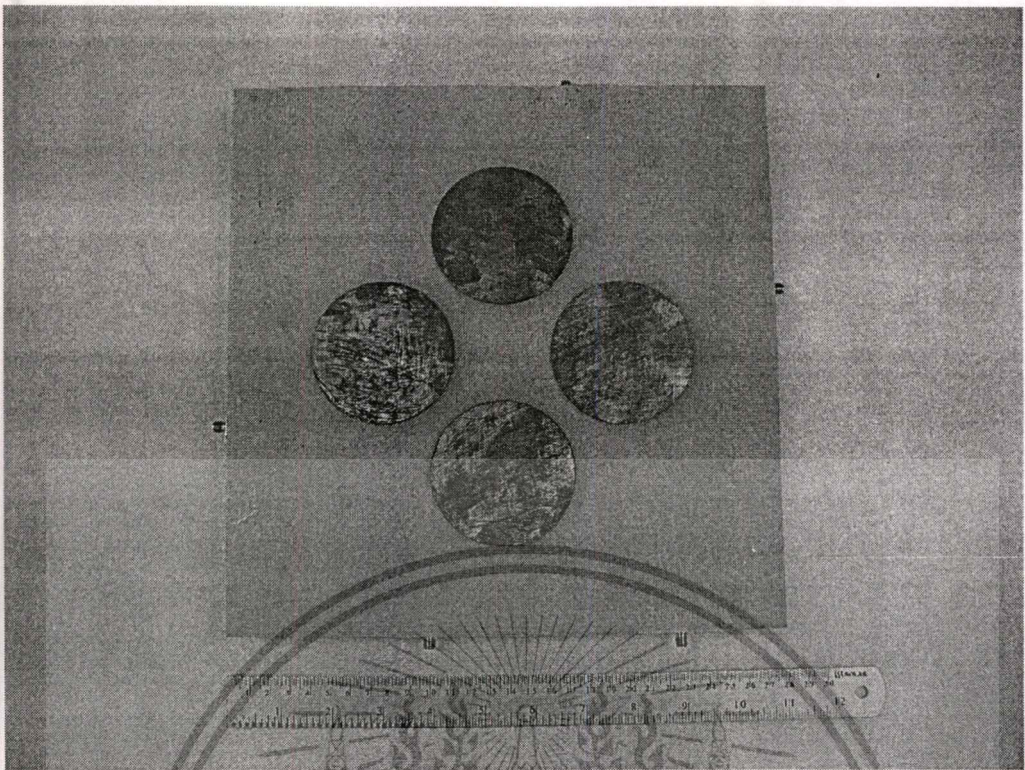
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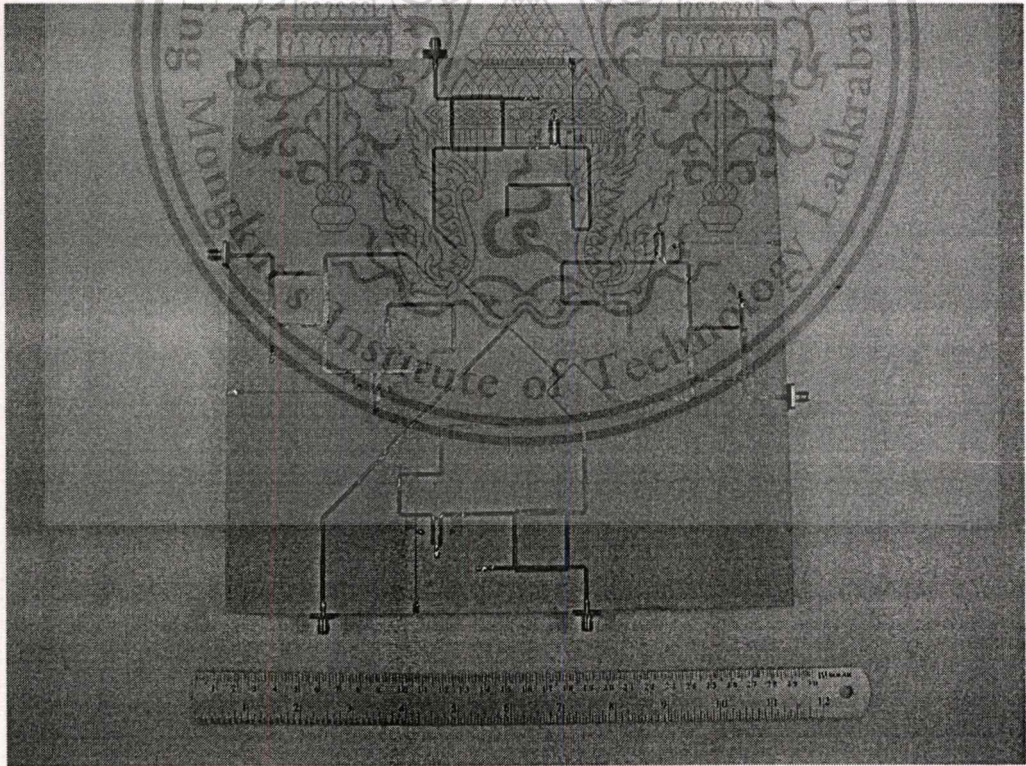
64 radiation patterns will be obtained for all four main beam directions. The four main beam directions can be obtained, and the adapted null patterns can be observed. Figure 3.8 and 3.9 show all radiation patterns of a phased array antenna of switched-beam elements that the main beam can be switched toward four directions and null pattern is adapted by changing the format of switched-beam elements (note that,  $x$  defined for reverse bias format and  $y$  for forward bias format). The solid line shows calculation pattern and dotted line shows experimental pattern. Prototype of a phased array antenna of switched-beam elements is illustrated in Figure 3.10.



**Figure 3.5** Radiation patterns of a flat four-beam compact phased array antenna, the solid lines show calculation patterns and dotted lines show experimental patterns: (a) main beam at  $45^\circ$  (b) main beam at  $135^\circ$  (c) main beam at  $225^\circ$  (d) main beam at  $315^\circ$ .



(a)



(b)

**Figure 3.6** Prototype of a flat four-beam compact phased array antenna: (a) antenna part, (b) feed structure and phase shifter part.

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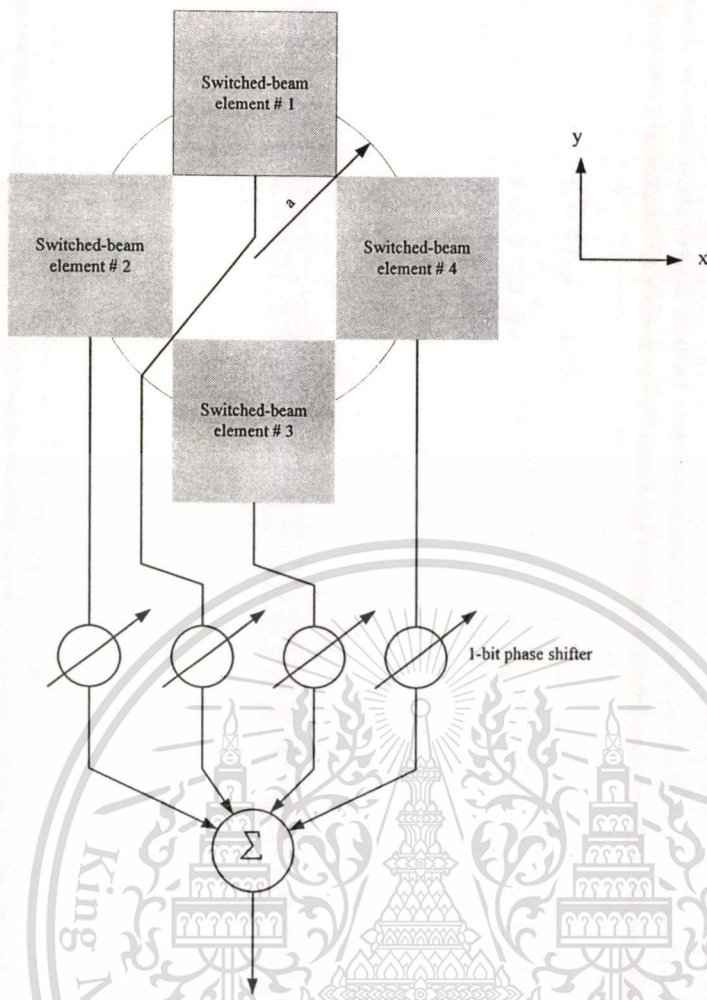


Figure 3.7 Configuration of a phased array antenna of switched-beam elements.

### 3.3 Performance of Switched-Beam Antenna

Increasing the capacity of a wireless communication system in the presence of limited spectrum is important. Indoor wireless or mobile communications differs from normal mobile communication in two important aspects, the interference environment and the multipath fading rate. The switched-beam antenna switches a number of fixed beams at the base station antenna site toward the user or mobile terminal. At the base station, the receiver selects the beam that provides the greatest signal enhancement and interference reduction to improve link capacity.

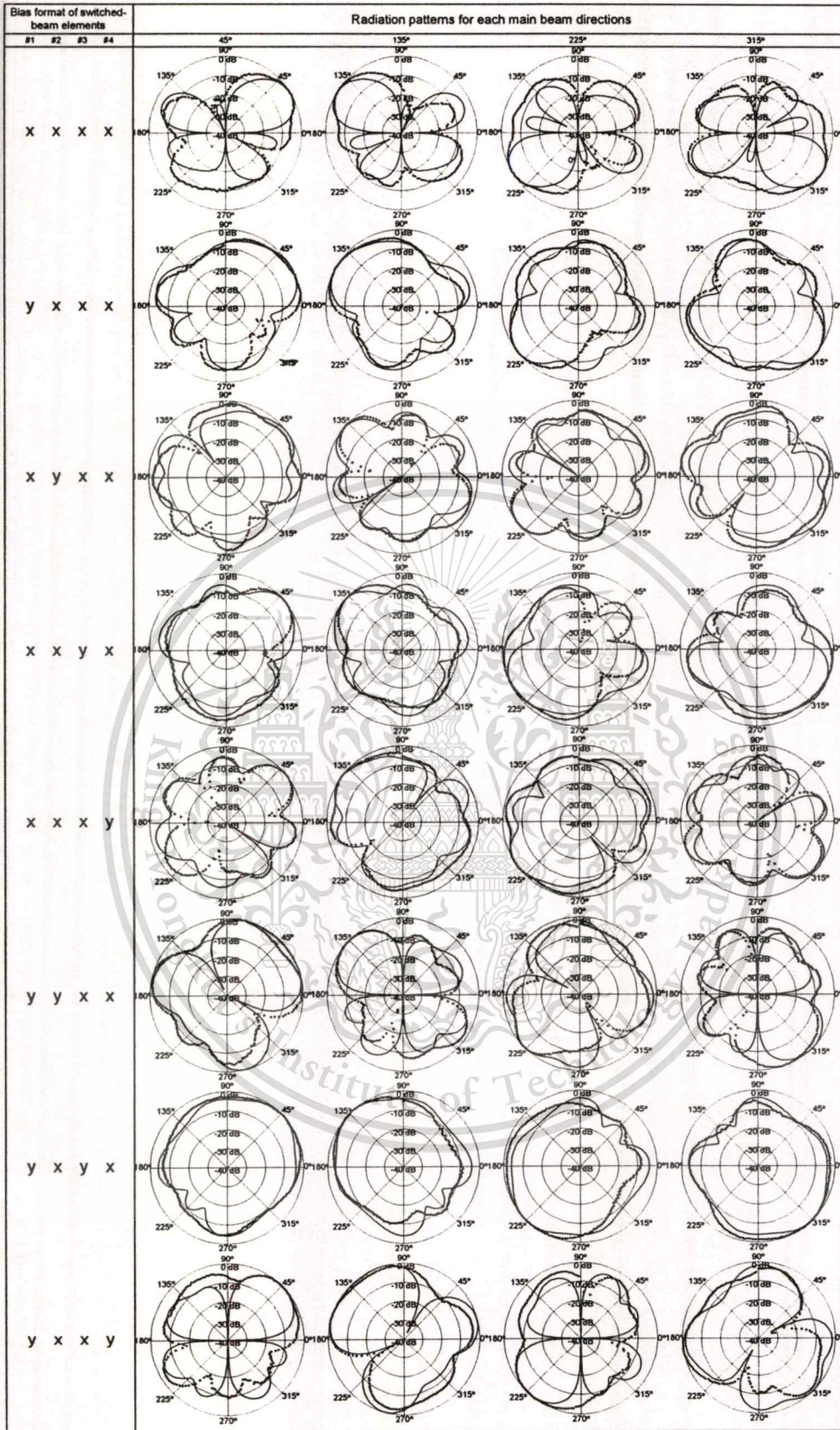


Figure 3.8 Radiation patterns of phased array antenna of switched-beam elements.

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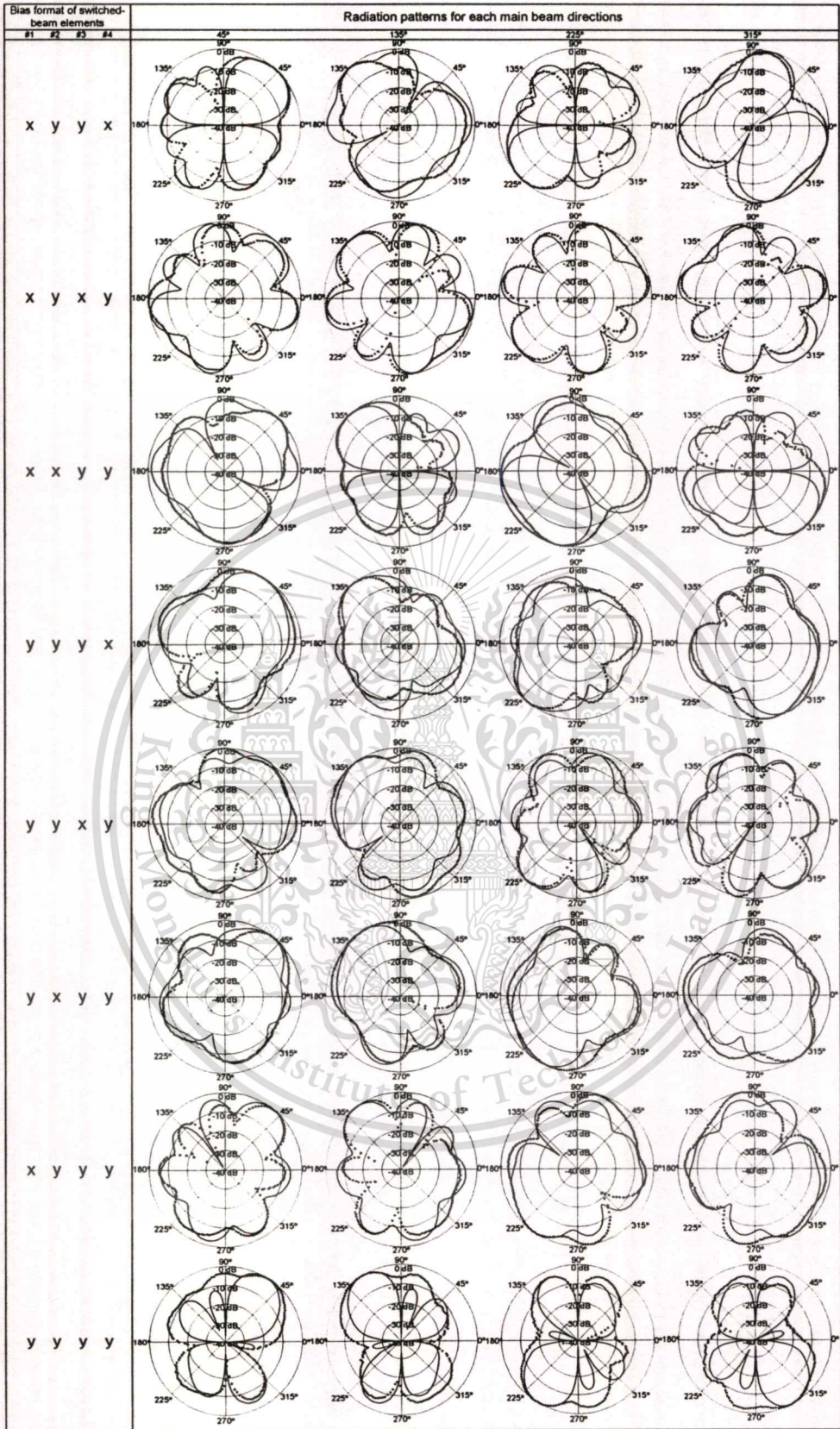
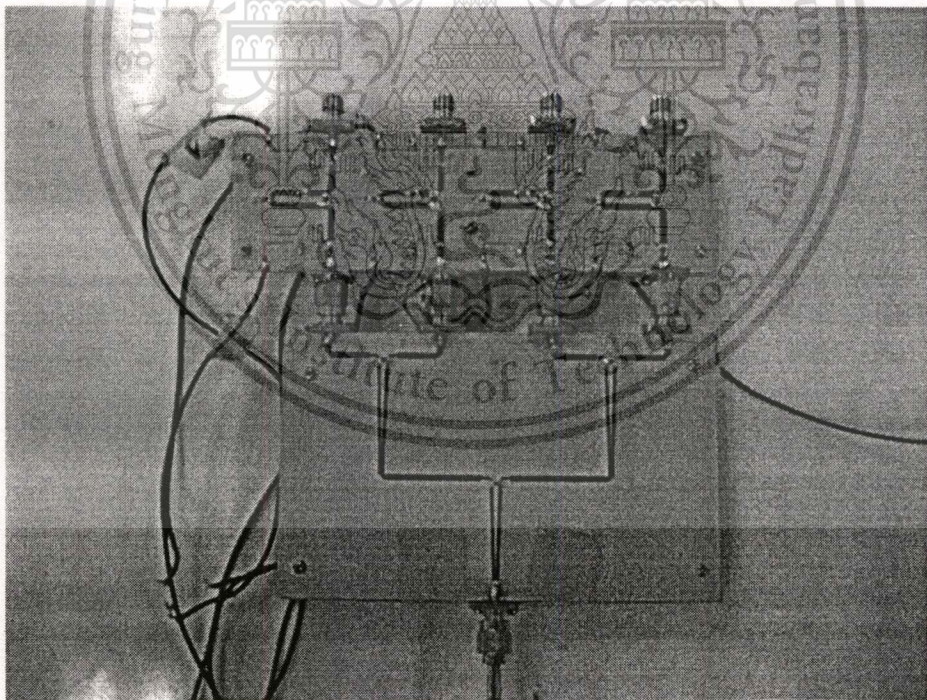
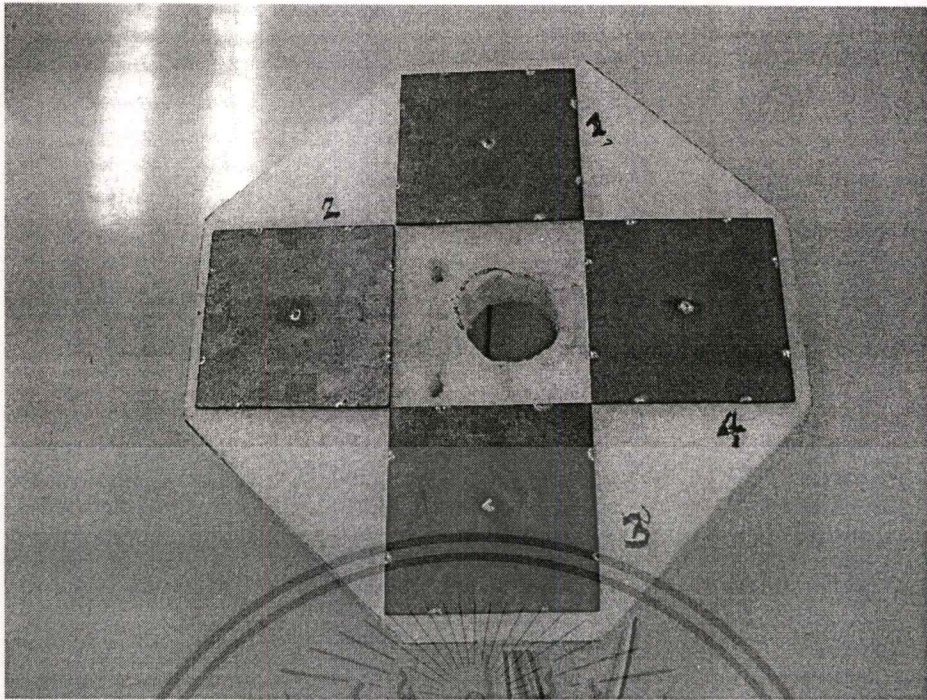


Figure 3.9 Radiation patterns of phased array antenna of switched-beam elements  
(continued).

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(b)

Figure 3.10 Prototype of a phased array antenna of switched-beam elements: (a) antenna part (b) 1-bit phase shifter and power combiner part.

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### 3.3.1 Capacity Enhancement

In the wireless communication network, the switched-beam smart antenna can be used to increase the capacity of an indoor wireless communication system by suppressing co-channel interference. The capacity can be increased by improving signal to interference ratio (SIR) at the base station, so that the multiple users can use the same channel simultaneously within a cell. However, since the propagation environments are different, the performance of a switched-beam antenna in indoor communications will be different from the mobile communications.

### 3.3.2 Interference Reduction and Rejection

To reduce interference, the directional beams of the switched-beam antenna are steered toward the mobile terminals. Interference to co-channel mobiles occurs only if they are within the narrow beamwidth of the directional beam of the switched-beam antenna. This reduces the probability of co-channel interference when compared with a system using omnidirectional base station antennas. Interference at the base station can be rejected using directional beams switched to mobile users and adapting nulls pattern to interfering co-channel users.

By using switched-beam antenna at the base station to communicate with mobile user on the downlink (see Figure 3.11), a base station (BS1) is less likely to interfere with nearby co-channel base stations than if it used an omnidirectional antenna. Interferences from co-channel base stations (BS2 and BS3) can be rejected by adapting null patterns to the directions of interferences. The SIR achieved by using switched-beam antenna is higher than using omnidirectional antenna at the base station. Therefore, improving in SIR, leading to capacity enhancement.

### 3.3.3 Multipath Mitigation

In most wireless channels, there are more than one propagation paths between transmitter and receiver, and the received signal consists of two or more components, each of which traveled in different paths from the transmitter. Each multipath component arrives with a delay that depends on the path length. Delayed multipath components can cause the intersymbol interference (ISI), and impose an upper limit on the data rate

that the channel can support without the use of expensive equalizers. Fading is another problem in a multipath channel. The multipath fading occurs because in general the multipath components arrive with different phases. At some points in space, the components cancel each other, causing deep fades in the received signal level. Both ISI and fading can be mitigated using the switched-beam antennas.

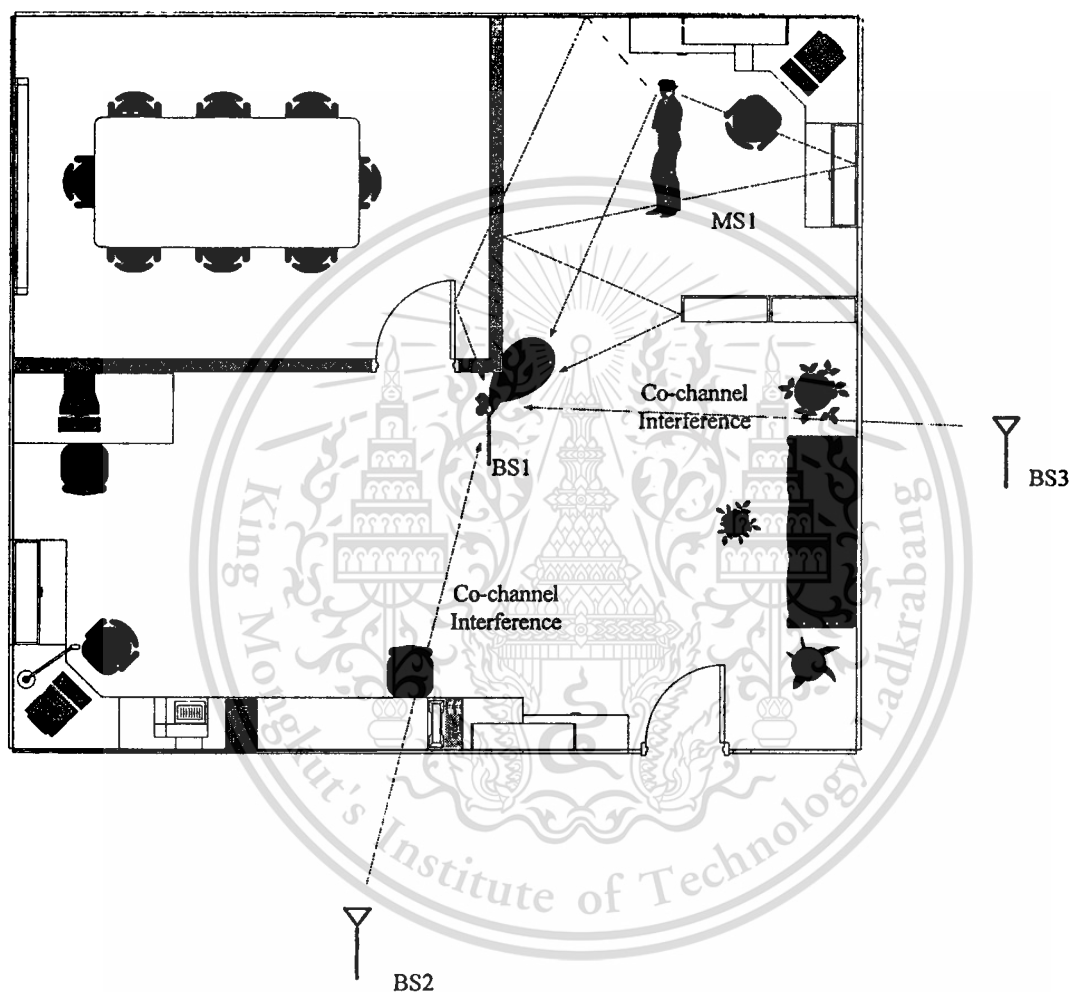


Figure 3.11 Co-channel interference can be rejected by using switched-beam antenna as the base station antenna.

### 3.4 Summary

This chapter presents the structure of switched-beam antennas, including the switched-beam single patch antenna, the flat four-beam compact phased array antenna and the phased array antenna of switched-beam elements. Usually, the switched-beam

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antenna is used as the base station antenna. The SIR can be improved by using switched-beam antenna. Interference at the base station can be rejected using directional beams switched to communicate with mobile users and adapting nulls pattern to interfering co-channel base station.



# CHAPTER 4

## SIMULATION OF MIMO INDOOR WIRELESS CHANNELS

### 4.1 Introduction

Information theory research has shown that large capacity gains over single antenna systems can be achieved when using MIMO antenna systems by exploiting multipath in the rich scattering wireless environment [9]. Capacity grows linearly with the number of antenna elements. Unfortunately, the MIMO system requires high cost of multiple radio transceivers at both transmitting and receiving sides. However, this drawback may be relieved by using switched-beam antenna. The switched-beam antenna offers multiple beams with more compact in size, as mentioned in the previous chapter. The channel capacities and correlation properties of the MIMO system using these switched-beam antennas are analyzed in this chapter.

### 4.2 MIMO Channel Models

In this chapter, we evaluate performance of the switched-beam antennas by using physical channel model. It is based on the scattering property of electromagnetic waves. At first, we study the performance of the switched-beam antennas by using one-ring scattering model. We found that the one-ring model is not appropriate for modeling indoor environment. It is suitable to model an outdoor environment. Then, the scattering geometry model is extended to include two scattering instants per path to improve model for indoor or picocell scenario. This model called is "two-ring" scattering model.

#### 4.2.1 One-Ring Scattering Model

To model multipath propagation and fading correlation, we extend the one-ring scattering model first employed by Jakes [15]. This model is appropriate in the fixed wireless communication systems, where a ring of scatterers is used to model local scattering around the user. The "one-ring" model is basically a ray tracing model. The spatial fading correlation of a narrowband flat fading channel can be determined from

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the physical parameters of the model, which includes antenna spacing, antenna arrangement, angle spread and angle of arrival.

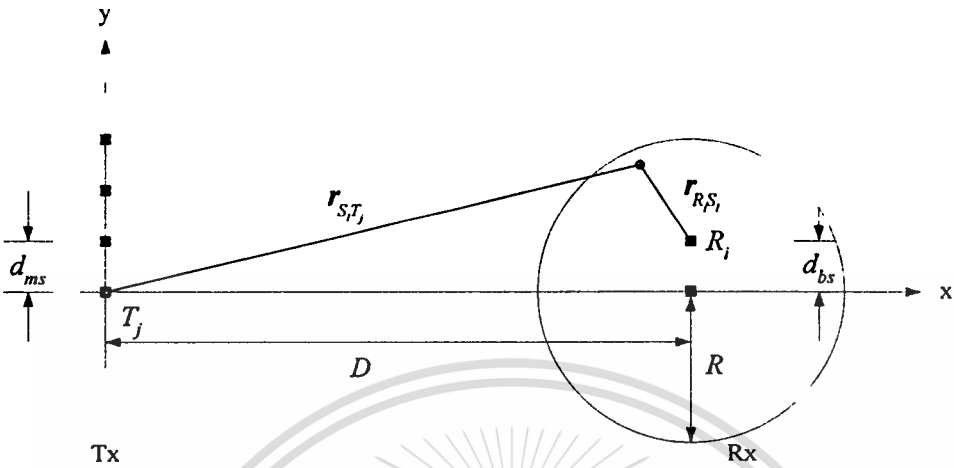


Figure 4.1 One-ring scattering model.

Figure 4.1 shows the one-ring scattering model, developed for MIMO communication system by Shiu and Svanesson [20, 21]. The scatterers are distributed uniformly within a circular ring of radius  $R$  centered at the base station. A transmitting array with  $T_j$  elements, aligned along the  $y$  axis is separated by a distance  $D$  along the  $x$  axis from a receiving array with  $R_i$  elements, whose elements are also aligned along the  $y$  axis. The element separations of the transmit and receive array are  $d_{ms}$  and  $d_{bs}$ , respectively.

#### 4.2.1.1 Channel Matrix

Consider the narrowband transmission of  $n_T$  statistically independent uniform power signals through a general one-ring model. The fading scattering environment with scatterers is assumed to be distributed in the farfield from the  $n_R$  receiver antennas, as shown in Figure 4.1, and then the channels occurring between transmitting side and receiving side are given by

$$H_{ij} = \sum_{l=1}^L \alpha_l e^{jk(r_{S_l T_j} + r_{R_i S_l})} g_{T_j}(\phi_l) g_{R_i}(\phi_l) \quad (4.1)$$

where the element of  $H_{ij}$  denotes the sub-channel from transmitter  $j$  to receiver  $i$ ,  $L$  is the number of scatterers.  $\alpha_l$  is a complex Gaussian distributed reflection coefficient

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with zero mean and unit variance.  $g_{T_j}(\phi_l)$  and  $g_{R_i}(\phi_l)$  are the radiation pattern of the transmitting and receiving antenna, respectively.  $r_{S_l T_j}$  and  $r_{R_i S_l}$  are the distance from transmitting antenna  $j$  to scatterer  $l$  and the distance from scatterer  $l$  to receiving antenna  $i$ , respectively.

#### 4.2.1.2 Simulation of Channel Capacity

The simulation results of the MIMO system by using switched-beam antennas first proposed in [22]. The realization of the channel matrix  $H$  is significant since the channel capacity is a function of channel matrix. The channel capacity of a MIMO system can be written as

$$C = \log_2 \left[ \det \left( I + \frac{\xi}{N} \cdot HH^H \right) \right] \quad \text{bps/Hz} \quad (4.2)$$

where  $\xi$  represents the signal-to-noise ratio (SNR).  $(\cdot)^H$  is the complex conjugate transpose of a channel matrix  $H$ , and  $I$  is the unit matrix. To find out the channel capacity obtained from the switched-beam antenna, a channel model that includes the impact of the radiation patterns and the interaction between transmitter and receiver is required. According to the channel model in the previous section, the channel capacities of the switched-beam antennas are calculated. The simulation parameters shown in Table 4.1.

Table 4.1 Simulation parameters of one-ring scattering model.

Parameter	Value
$f_c$	1.95 GHz
$D$	5 m.
$R$	4m.
$L$	20
$d_{bs}, d_{ms}$	$\lambda/2$

Firstly, the system comprising single transmitting antenna and multiple receiving antennas, known as single-input multiple-output (SIMO) system, is considered. The

channel capacity of this system using switched-beam antenna is computed by applying the switched-beam antenna as the multiple receiving antennas and a monopole antenna as a transmitting antenna. The capacity with various SNRs is shown in Figure 4.2. It is obvious that the higher SNR, the higher capacity. The channel capacity of the SIMO system using switched-beam single patch antenna, flat four-beam phased array antenna and phased array antenna of switched-beam elements as well as monopole antenna are compared. For illustrative purpose, a 20dB SNR is used. It can be seen that a monopole antenna and the switched-beam single patch antenna provide the capacity of 6.66 bps/Hz and 6.69 bps/Hz, respectively, at 20dB SNR. For the flat four-beam phased array antenna, the capacity of 7.19 bps/Hz is found, while the phased array antenna of switched-beam elements can provide the capacity of 8.89 bps/Hz. It is found that the switched-beam antennas can increase the capacity of the system when compared with a monopole antenna. However, increase of capacity is not significant because only one transmitting antenna is used.

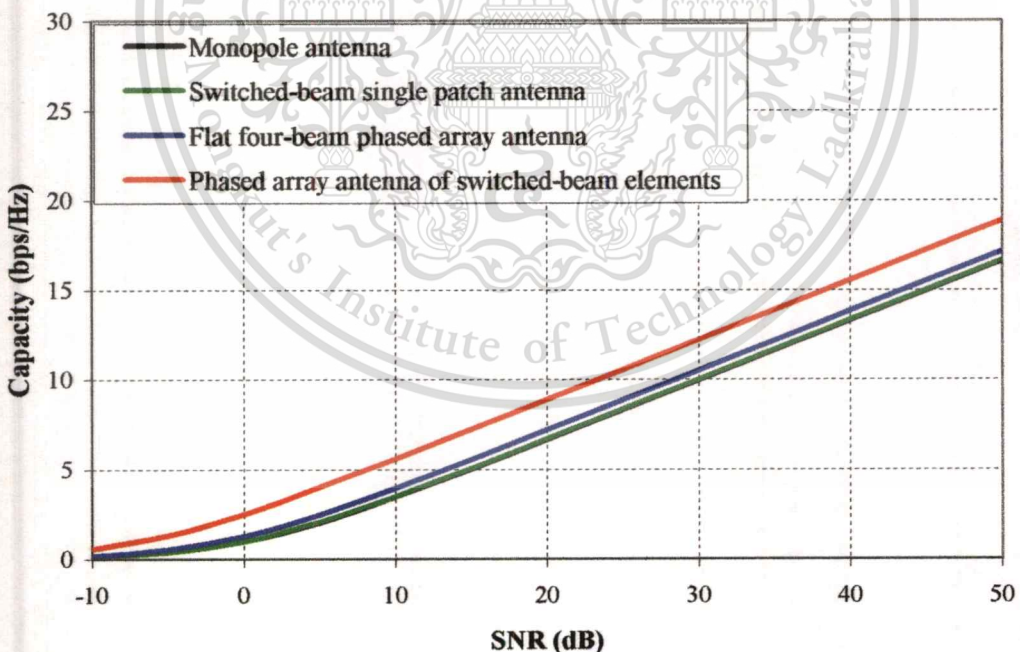


Figure 4.2 Capacity of SIMO system using switched-beam antenna.

Considering the channel capacity of MIMO system using switched-beam antenna, two and four elements of monopole antenna are assumed as the transmitting antenna. This material is reserved for educational use only, not allowed for commercial use.

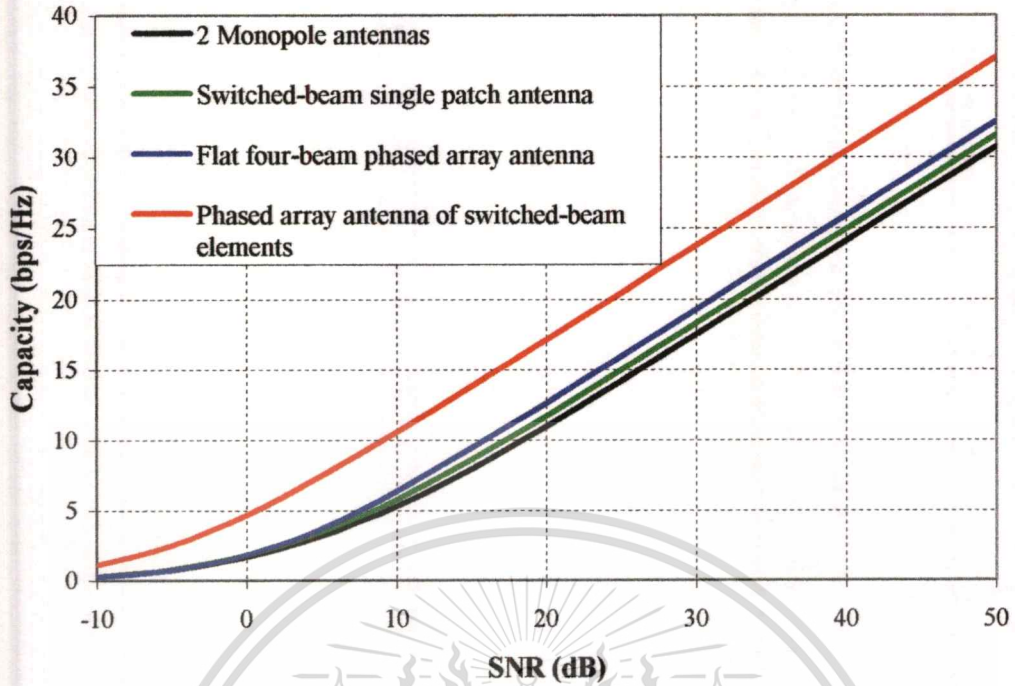


Figure 4.3 Capacity of MIMO system using switched-beam antenna with two-element transmitting antenna.

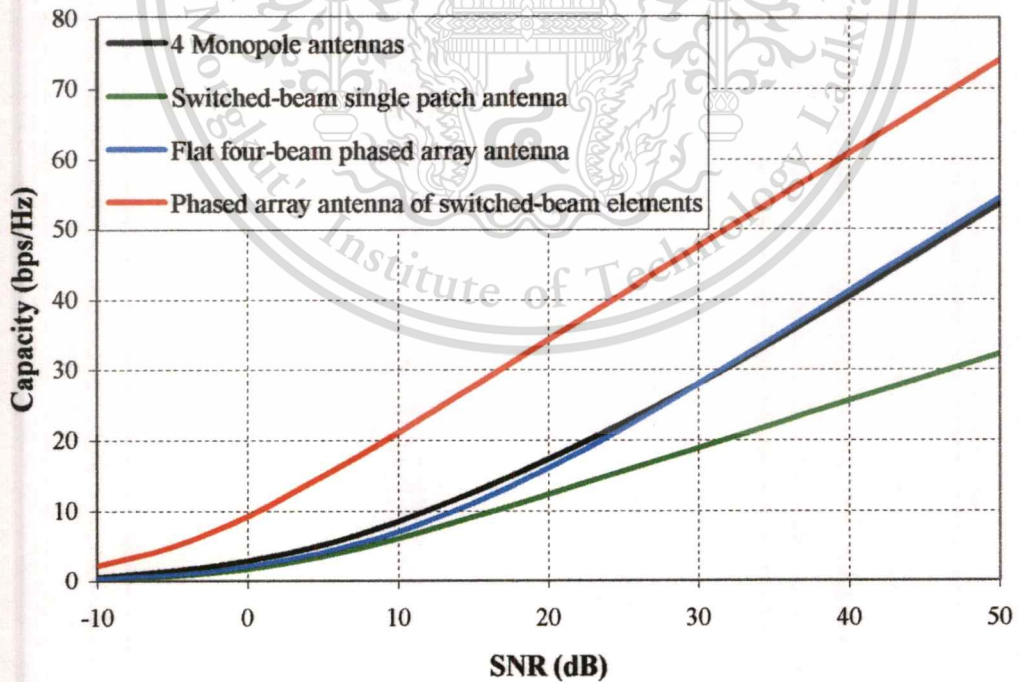


Figure 4.4 Capacity of MIMO system using switched-beam antenna with four-element transmitting antenna.

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antennas. The results can be illustrated in Figure 4.3 and Figure 4.4, respectively. In case of two-element transmitting antenna, the channel capacities for two monopole antennas, the switched-beam single patch antenna, the flat four-beam phased array antenna and the phased array antenna of switched-beam elements are 10.98, 11.73, 12.66 and 17.14 bps/Hz, respectively. The capacities given by the switched-beam antennas are higher than two monopole antennas. Compared with the case of single transmitting antenna (SIMO system), the capacities are 4.32, 5.04, 5.47 and 8.25 bps/Hz increased. For the case of four-element transmitting antenna, the channel capacities are 17.35, 12.32, 16.08 and 34.25 bps/Hz, respectively. The capacities are 10.69, 5.63, 8.89, 25.36 bps/Hz enhanced relative to SIMO system. However, it was found that the capacity given by four monopole antennas is higher than the capacity given by the switched-beam single patch antenna and the flat four-beam phased array antenna. Since the switched-beam single patch antenna can provide two radiation patterns, the sub-channel obtained from this antenna is lower than that of the four monopole antennas. Also, the flat four-beam phased array antenna provides lower capacity than the four monopole antennas, since correlation between the four switched-beam tends to be larger than the radiation patterns of the four monopole antennas with  $\lambda/2$  inter-element spacing. However, the phased array antenna of switched-beam antenna can give higher capacity than four monopole antennas, since 64 radiation patterns can increase much more sub-channel than four monopole antennas.

The complementary cumulative distribution function (CCDF) of capacity of MIMO system using switched-beam antenna with two-element transmitting antenna and four-element transmitting antenna are plotted in Figure 4.5 and Figure 4.6, respectively, at an SNR of 20 dB. With two-element transmitting antenna, two monopole antennas and the switched-beam single patch antenna have almost the same performance that capacity exceeds 7 bps/Hz at 90 % probability. The flat four-beam phased array antenna and the phased array antenna of switched-beam elements show higher capacity of 8.5 and 16 bps/Hz, respectively, at 90 % probability. In case of four-element transmitting antenna, the CCDF of capacity shows that the performance of four monopole antennas is greater than the switched-beam single patch antenna and the flat four-beam phased array antenna with the capacity more than 15.5 bps/Hz, whereas the capacities of the

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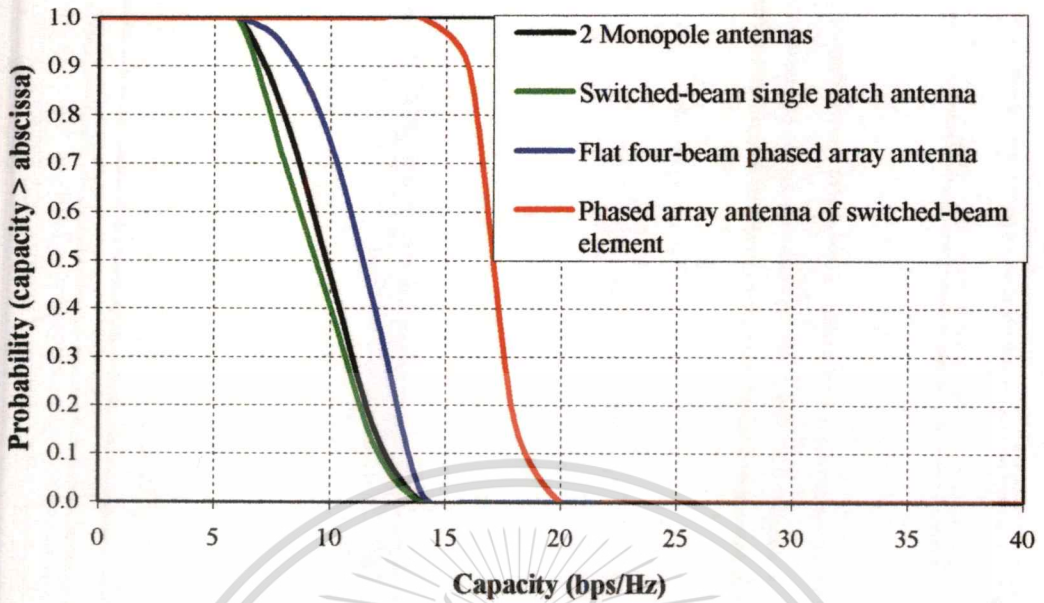


Figure 4.5 The CCDF of MIMO system using switched-beam antenna with two-element transmitting antenna.

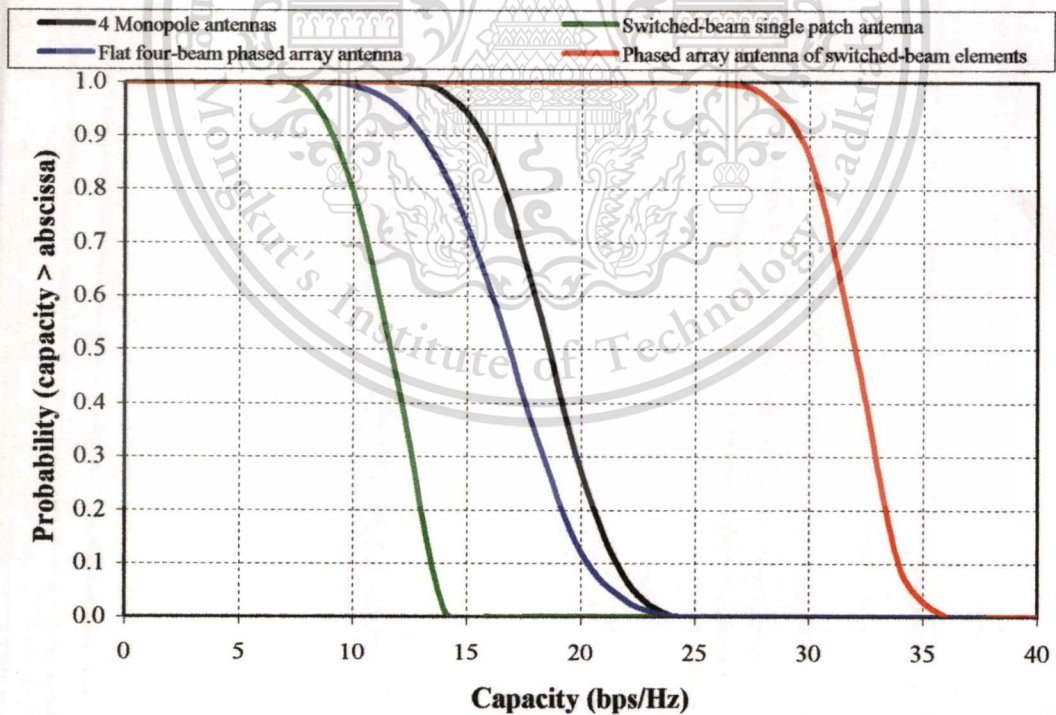


Figure 4.6 The CCDF of MIMO system using switched-beam antenna with four-element transmitting antenna.

switched-beam single patch antenna and the flat four-beam phased array antenna are more than 9 and 13 bps/Hz, respectively, at 90 % probability. However, the capacity of four monopole antennas is lower than the phased array antenna of switched-beam elements that capacity exceeds 29.5 bps/Hz.

#### 4.2.2 Two-Ring Scattering Model

In a typical realistic indoor application scenario, both the transmit and receive antennas of the MIMO system are surrounded by local scatterers, therefore, we utilize the correlated fading two-ring channel model proposed by Svantesson [23]. In this work, we reduce some parameters from Svantesson's model, such as cluster group and multi-polarized to obtain a channel model that still contain physical insight while simple enough to be applicable in the system performance simulations.

The two-ring scattering model is shown in Figure 4.7, where we have shown a particular path from transmitting antenna to receiving antenna via a local scatterer at the transmitting and receiving array. At the transmitting side, the signals from transmitting antenna are reflected at the scatterer points in the ring of scatterers before traveling to the receiving side. At the receiving side, the signals from the transmitting side are reflected at the scatterer points in the ring of scatterers before incoming to the receiving antenna. The scatterers are placed close to both the transmitting and receiving arrays, which are separated by a distance  $D$ . The transmitter consists of  $T_j$  transmitting antennas located within a circular ring of radius  $R$ . Similarly, at the receiver, there are  $R_i$  antennas within a circular ring of radius  $R$ .  $d_{ms}$  and  $d_{bs}$  is an inter-element spacing of the antennas at the mobile station and the base station, respectively. The distance from transmitting antenna  $j$  to the local scatterer  $l$  at the transmitting side is denoted by  $r_{S_T, T_j}$ . The distance from the local scatterer  $l$  at the transmitting side to the local scatterer  $l$  at the receiving side is denoted by  $r_{S_R, S_T, l}$ . The distance from the local scatterer  $l$  at the receiving side to the receiving antenna  $i$  is denoted by  $r_{R_i, S_R, l}$ . In this work, we apply the switched-beam antenna as the multiple receiving antenna and monopole array as the transmitting antenna.

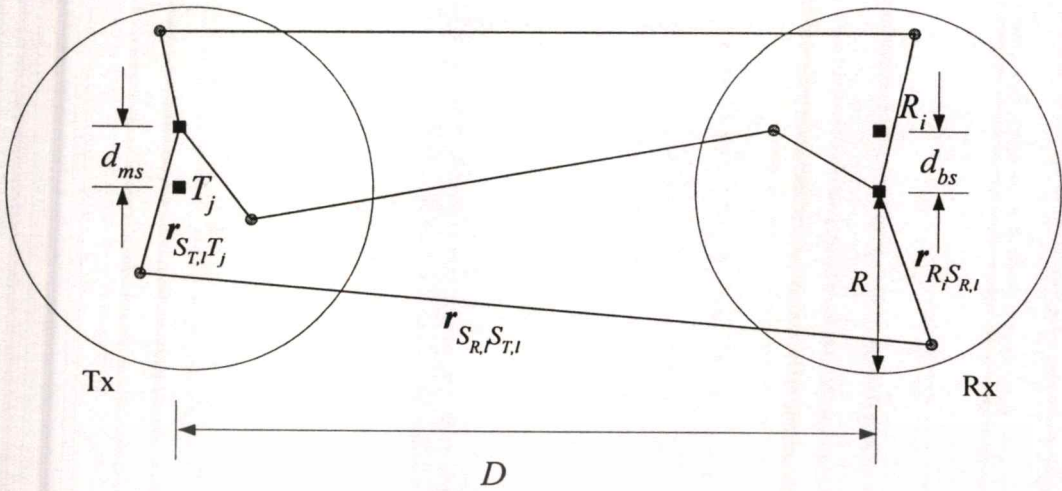


Figure 4.7 Two-ring scattering model.

#### 4.2.2.1 Channel Matrix

Assuming, the scatterers are located on two circular rings around both Tx and Rx. The transmitted signal from the transmitting antenna reach one of scatterers at the transmit ring and reach one of scatterers at the receive ring and then impinges on the receiving antenna. The complex channel impulse response between the transmitting side and the receiving side are given by

$$H_{ij} = \sum_{l=1}^L \alpha_{T,l} \alpha_{R,l} e^{jk(r_{S_{T,l}T_j} + r_{S_{R,l}S_{T,l}} + r_{R_iS_{R,l}})} g_{T_j}(\phi_l) g_{R_i}(\phi_l) \quad (4.3)$$

where  $H_{ij}$  denotes the channel coefficient between the transmit antenna  $j$  and the receive antenna  $i$ .  $\alpha_{T,l}$  and  $\alpha_{R,l}$  denote the complex Gaussian distributed transmit and receive scattering coefficient of path  $l$ . Furthermore,  $r_{S_{T,l}T_j}$ ,  $r_{S_{R,l}S_{T,l}}$  and  $r_{R_iS_{R,l}}$  denote the distance from the transmitting antenna  $j$  to the scatterer  $l$  at the transmit ring, the distance from the scatterer  $l$  at the transmit ring to the scatterer  $l$  at the receive ring and the distance from the scatterer  $l$  at the receive ring to the receive antenna  $i$ . Finally,  $g_{T_j}(\phi_l)$  and  $g_{R_i}(\phi_l)$  denote the radiation pattern of the transmitting and the receiving antennas.

#### 4.2.2.2 Simulation of Channel Capacity

The performance of MIMO systems with a uniform linear array (ULA) of monopole antenna at the transmitter and switched-beam antenna at the receiver has been investigated in an indoor environment by using two-ring scattering model.

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According to the channel model in the previous section, the channel capacities of the switched-beam antennas are calculated by using the same simulation parameters in Table 4.1.

Consider the system with two transmitting antennas and multiple receiving antennas. The channel capacity of this system using switched-beam antenna is computed by applying the switched-beam antenna as the multiple receiving antenna and monopole antenna array as the transmitting antenna. Figure 4.8 shows the capacity as a function of SNR received at the receiver for a fixed distance communication. For illustrative purpose, a 20 dB SNR is used. The capacities almost increase linearly with increase in SNR. In case of two-element transmitting antenna, the channel capacities for two monopole antennas, the switched-beam single patch antenna, the flat four-beam phased array antenna and the phased array antenna of switched-beam elements are 7.62, 6.99, 12.69 and 16.57 bps/Hz, respectively. Figure 4.9 shows the case of four-element transmitting antenna, the channel capacities are 18.23, 9.11, 12.88 and 28.88 bps/Hz, respectively. The capacities are 10.61, 2.12, 0.19, 12.31 bps/Hz enhanced relative to MIMO system with two transmitting antennas.

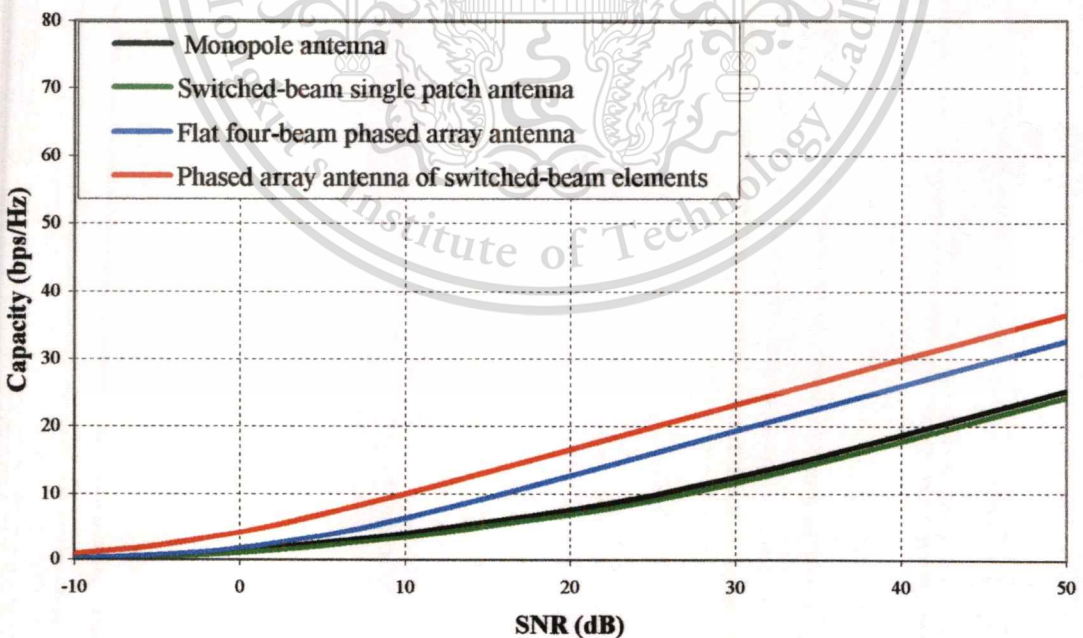
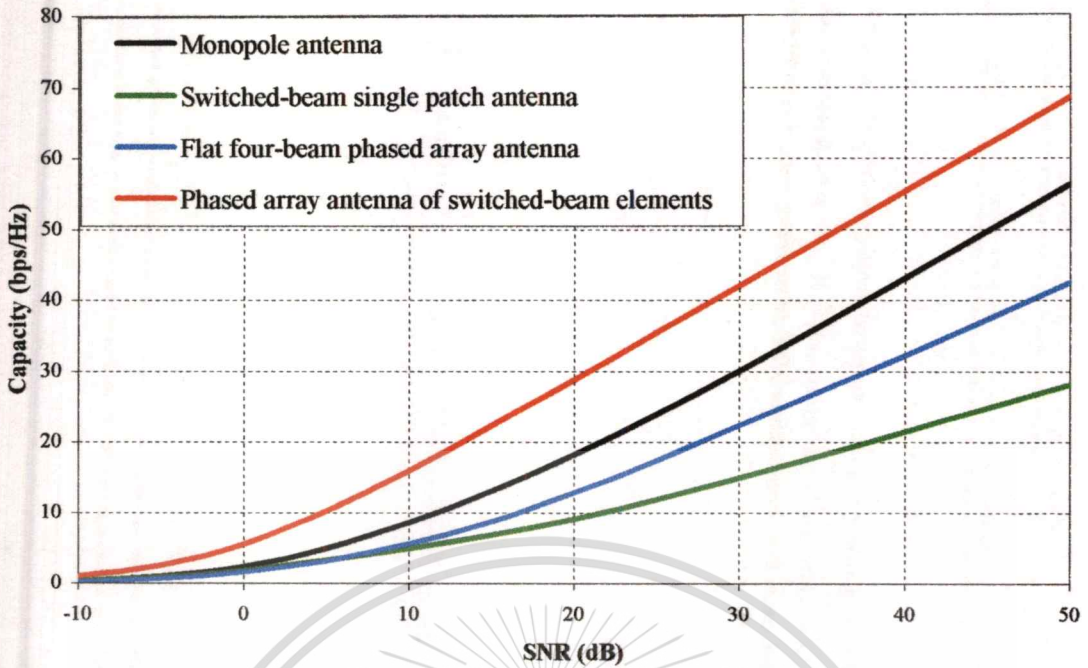


Figure 4.8 Capacity of MIMO system using switched-beam antenna with two-element transmitting antenna.



**Figure 4.9** Capacity of MIMO system using switched-beam antenna with four-element transmitting antenna.

The CCDF of capacity of MIMO system using switched-beam antenna with two-element transmitting antenna and four-element transmitting antenna based on two-ring model are plotted in Figure 4.10 and Figure 4.11, respectively, at an SNR of 20 dB. With two-element transmitting antenna, two-monopole antenna and the switched-beam single patch antenna have almost the same performance that capacity exceeds 6.5 bps/Hz at 90 % probability. The flat four-beam phased array antenna and the phased array antenna of switched-beam elements show higher capacity of 8.5 and 15.5 bps/Hz, respectively, at 90 % probability. In case of four-element transmitting antenna, the CCDF of capacity shows that the performance of four monopole antennas is greater than the switched-beam single patch antenna and the flat four-beam phased array antenna with the capacity more than 15 bps/Hz, whereas the capacities of the switched-beam single patch antenna and the flat four-beam phased array antenna are more than 9 and 12.5 bps/Hz, respectively, at 90 % probability. However, the capacity of four monopole antennas is lower than the phased array antenna of switched-beam elements that capacity exceeds 28.5 bps/Hz.

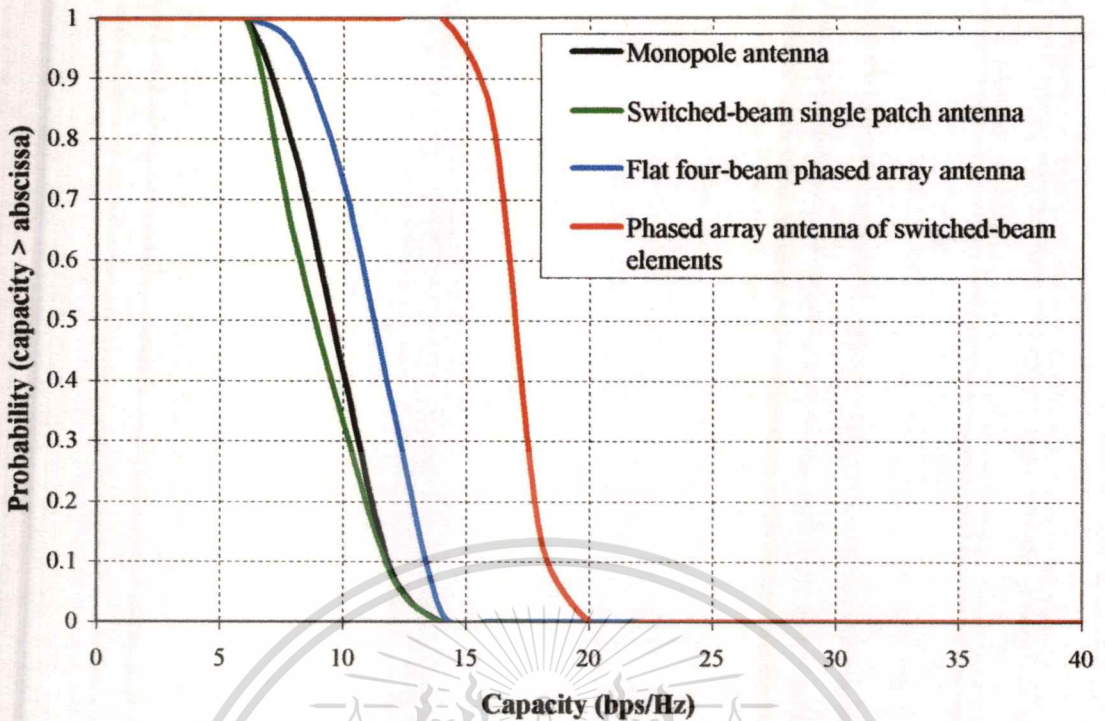


Figure 4.10 The CCDF of MIMO system using switched-beam antenna with two-element transmitting antenna based on two-ring model.

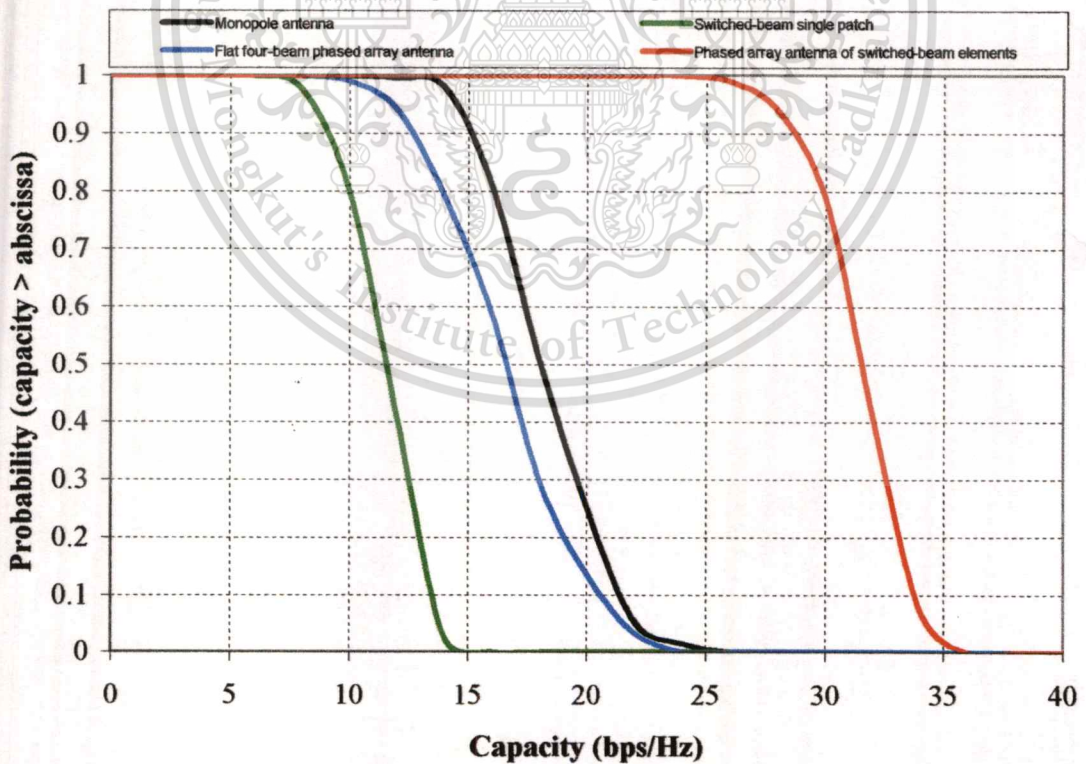


Figure 4.11 The CCDF of MIMO system using switched-beam antenna with four-element transmitting antenna based on two-ring model.

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### 4.2.3 Comparison of One-Ring and Two-Ring Models

The capacities results of the one-ring model and the two-ring model by using two and four transmitting antennas are compared in Figure 4.12 and Figure 4.13, respectively. It was found that the capacity given by the one-ring model is higher than the capacity given by the two-ring model, because in the one-ring model the transmitting antenna must be located at the height over the floor or surrounding, so that no scatterers appeared in the model. The transmitted signal of the one-ring model is attenuated only at the receive-ring and the propagation distance is shorter than the two-ring model. In an indoor environment both the transmitting and the receiving antennas are placed near the walls, the floor or the ceiling, so that the scatterers are appeared in both the transmitter and the receiver sides. Consequently, higher attenuated in the received signal in the two-ring model. In the further study, we focus only on the two-ring scattering model.

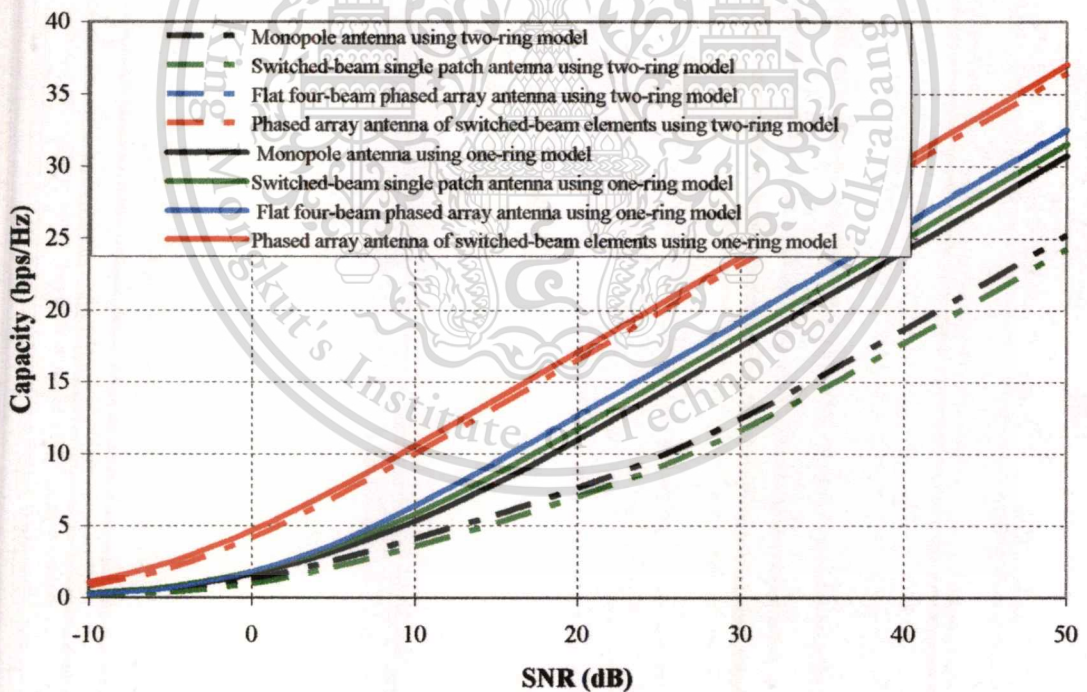


Figure 4.12 Comparison of the capacity of MIMO system by using one-ring and two-ring model with two-element transmitting antenna.

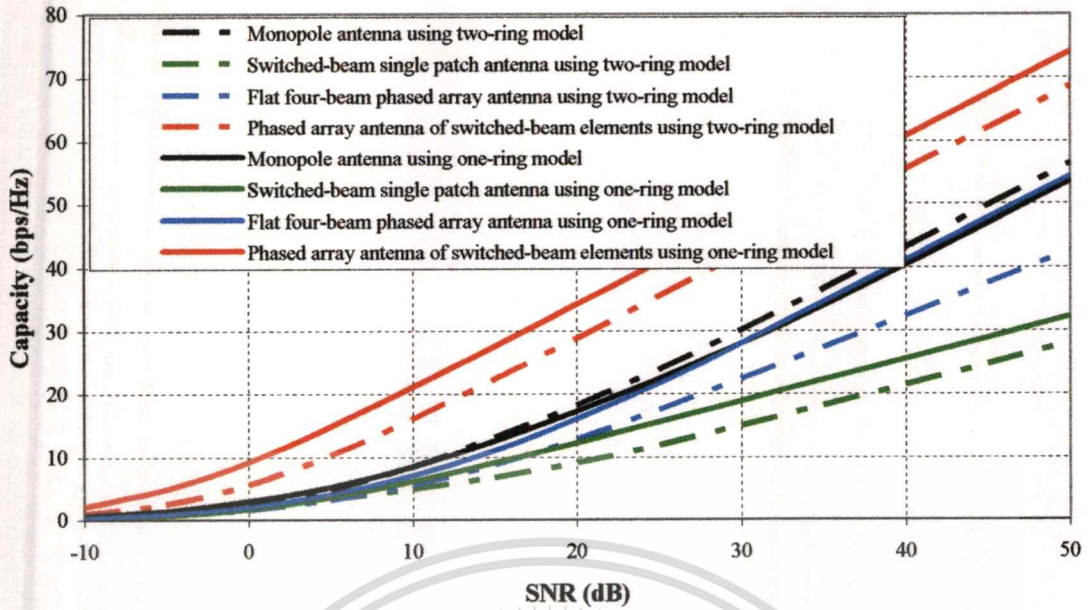


Figure 4.13 Comparison of the capacity of MIMO system by using one-ring and two-ring model with four-element transmitting antenna.

### 4.3 MIMO Correlation

The spatial correlation properties in the MIMO wireless channel are obtained by the Kronecker product of two independent correlation matrices defining the correlation properties at the MS and BS sides, respectively [16]. The spatial complex correlation coefficient at the MS between antenna  $m_1$  and  $m_2$  is given by

$$\rho_{m_1 m_2}^{MS} = \langle H_{m_1 n}, H_{m_2 n} \rangle. \quad (4.4)$$

It is assumed that the correlation function at the MS is independent of the antenna elements  $n$  at the opposite side.

The spatial complex correlation coefficient observed at the BS is similarly defined as

$$\rho_{n_1 n_2}^{BS} = \langle H_{m n_1}, H_{m n_2} \rangle \quad (4.5)$$

and assumed to be independent of  $m$  at the MS.

From (4.4) and (4.5), we can define the complex correlation matrices

$$R_{MS} = \begin{bmatrix} \rho_{11}^{MS} & \rho_{12}^{MS} & \cdots & \rho_{1M}^{MS} \\ \rho_{21}^{MS} & \rho_{22}^{MS} & \cdots & \rho_{2M}^{MS} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{M1}^{MS} & \rho_{M2}^{MS} & \cdots & \rho_{MM}^{MS} \end{bmatrix} \quad (4.6)$$

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and

$$R_{BS} = \begin{bmatrix} \rho_{11}^{BS} & \rho_{12}^{BS} & \cdots & \rho_{1N}^{BS} \\ \rho_{21}^{BS} & \rho_{22}^{BS} & \cdots & \rho_{2N}^{BS} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{N1}^{BS} & \rho_{N2}^{BS} & \cdots & \rho_{NN}^{BS} \end{bmatrix}. \quad (4.7)$$

The spatial correlation matrix of the MIMO wireless channel is the Kronecker product of the spatial correlation matrix at the MS and the BS and is given by

$$R_{MIMO} = R_{MS} \otimes R_{BS} \quad (4.8)$$

where  $\otimes$  represents the Kronecker product.

#### 4.4 Case Study of Switched-Beam Antennas

At this section, the performance of a switched-beam single patch antenna has been evaluated for a  $2 \times 2$  MIMO indoor wireless channel by using two-ring model. The performances of the phased array antenna of switched-beam elements and the flat four-beam phased array antenna have been evaluated for a  $4 \times 4$  MIMO indoor wireless channel.

##### 4.4.1 $2 \times 2$ MIMO Channel

For a switched-beam single patch antenna, the channel capacity for a  $2 \times 2$  MIMO channel is illustrated in (4.8) in the previous section. Note that the capacity of a switched-beam single patch antenna is lower than the capacity of two monopole antennas, because the monopole antenna has omnidirectional pattern while a switched-beam single patch has bidirectional pattern. Consequently, the monopole antenna can receive all incoming signal form a circular ring of scatterer, so that the capacity is higher than a switched-beam single patch antenna. Monte-Carlo computer simulation has been used to generate 200 channel realizations and the CCDF of the simulated channel capacity is compared in Figure 4.10 in the previous section. From the figure, the capacity of the two monopole antenna exceeds 7 bps/Hz at 90 % probability and also higher than a switched-beam single patch antenna by 0.5 bps/Hz. The magnitude of the envelop correlation matrix for a  $2 \times 2$  MIMO indoor wireless channel is calculated by using (4.8). The results are given in Figure 4.14 and 4.15. Clearly, a  $2 \times 2$  MIMO channel has fully correlated channel coefficient.

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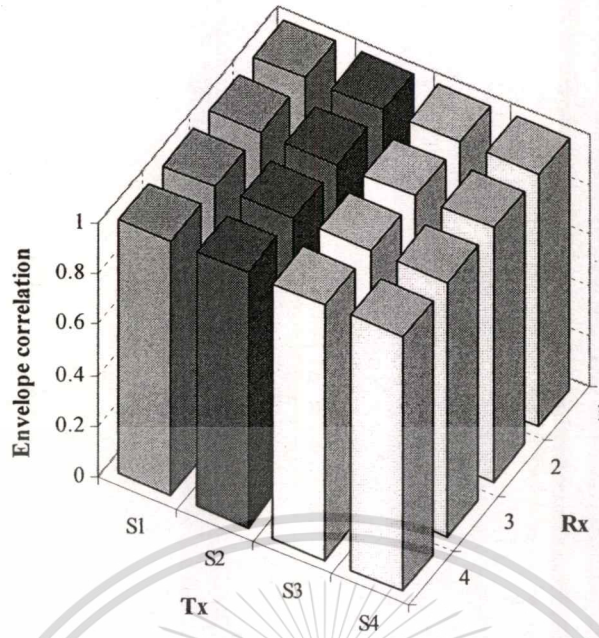


Figure 4.14 The magnitude of the envelope correlation matrix for a  $2 \times 2$  MIMO system using the uniform linear array monopole antennas at both the transmitting and the receiving side.

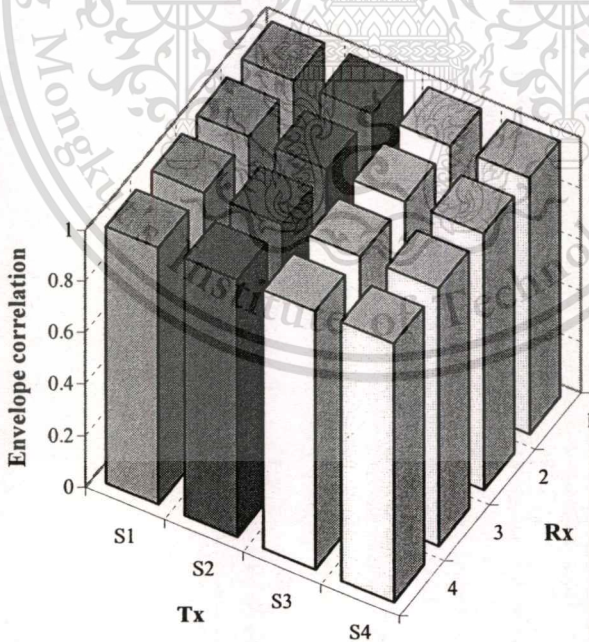


Figure 4.15 The magnitude of the envelope correlation matrix for a  $2 \times 2$  MIMO system using the uniform linear array monopole antennas at the transmitting side and a switched-beam single patch antenna at the receiving side.

#### 4.4.2 $4 \times 4$ MIMO Channel

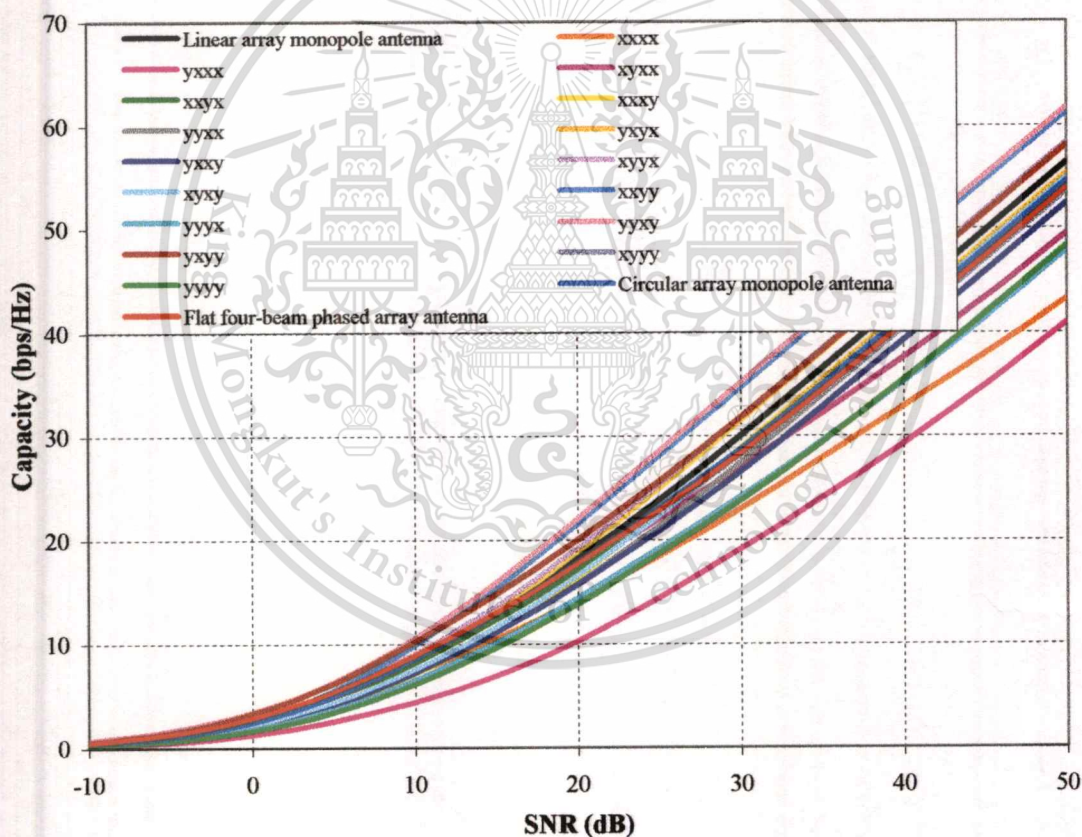
A phased array antenna of switched-beam elements and a flat four-beam phased array antenna are evaluated for a  $4 \times 4$  MIMO indoor wireless channel. Firstly, four elements of monopole antenna are assumed as the transmitting antennas and a phased array antenna of switched-beam element is used as the receiving antenna. In this case, the radiation patterns of the receiving antenna are switched to four main beam directions,  $45^\circ$ ,  $135^\circ$ ,  $225^\circ$  and  $315^\circ$ , respectively. The phased array antenna of switched-beam elements is performed in all 16 bias formats. Thus, it can be implied that there are sixteen  $4 \times 4$  MIMO channels for a phased array antenna of switched-beam elements. Next, a flat four-beam phased array antenna is assumed as the receiving antenna. The radiation patterns of a flat four-beam phased array antenna are switched to all four main beam directions to generate a  $4 \times 4$  MIMO channel. Note that the phased array antenna of switched-beam element and the flat four-beam phased array antenna is a uniform circular array, so that four-element uniform circular array of monopole antenna is used as receiving antennas to compare with both switched-beam antennas.

Figure 4.16 shows the capacity as a function of SNR received at the BS for a fixed distanced wireless communication. The channel capacity with 20 dB SNR is illustrated in Table 4.2. For a phased array antenna of switched-beam elements, the capacity level varies from 10.363 bps/Hz to 22.105 bps/Hz depends on the bias format. There are 5 bias formats that the channel capacity obtained are higher than the channel capacity given from the four-element UCA of monopole antenna and the four-element ULA of monopole antenna. For a flat four-beam phased array antenna, the channel capacity obtained is closed to the channel capacity given from the four-element UCA of monopole antenna and the four-element ULA of monopole antenna.

The CCDF of capacity of MIMO system using switched antenna for a  $4 \times 4$  MIMO channel is plotted in Figure 4.17, at an SNR of 20 dB. At 90 % probability, the channel capacities of switched-beam antennas are exceeds 11 bps/Hz, but lower than the four-element ULA and UCA of monopole antenna.

The magnitude of the envelope correlation matrix, that is a normalization of the correlation matrix for a  $4 \times 4$  MIMO indoor wireless channel by using the four-element

ULA of monopole antenna, four-element UCA of monopole antenna, a flat four-beam phased array antenna and a phased array antenna of switched-beam elements at the receiving side are illustrated from Figure 4.18 to Figure 4.36. An example of the correlation, consider Figure 4.18, the correlation properties between the base station (Rx) and the mobile station (Tx) for a  $4 \times 4$  MIMO indoor wireless channel with an average magnitude of envelope correlation of 0.45. It is preferable that the envelope correlation lower than 0.7 for practical use in wireless communication systems [3, 15]. Clearly, for a  $4 \times 4$  MIMO indoor wireless channel has medium correlated channel coefficient. Thus, in this case the channel characteristic is presented as the correlated channel.



**Figure 4.16** Capacity of MIMO system using phased array antenna of switched-beam elements for all 16 bias formats.

**Table 4.2** The channel capacity of a phased array antenna of switched-beam elements and a flat four-beam phased array antenna with 20 dB SNR.

Antenna Configuration	Channel Capacity (bps/Hz)
Switched-beam elements xxxx	14.273
Switched-beam elements yxxx	10.363
Switched-beam elements xyxx	17.218
Switched-beam elements xxyx	17.224
Switched-beam elements xxxy	18.891
Switched-beam elements yyxx	15.870
Switched-beam elements yxyx	16.495
Switched-beam elements yxxy	15.807
Switched-beam elements xyxx	19.245
Switched-beam elements xyxy	16.658
Switched-beam elements xxyy	21.662
Switched-beam elements yyyx	14.469
Switched-beam elements yyxy	22.105
Switched-beam elements yxyy	20.079
Switched-beam elements xyyy	17.711
Switched-beam elements yyyy	13.956
Flat four-beam	17.780
4 elements UCA	17.892
4 elements ULA	18.234

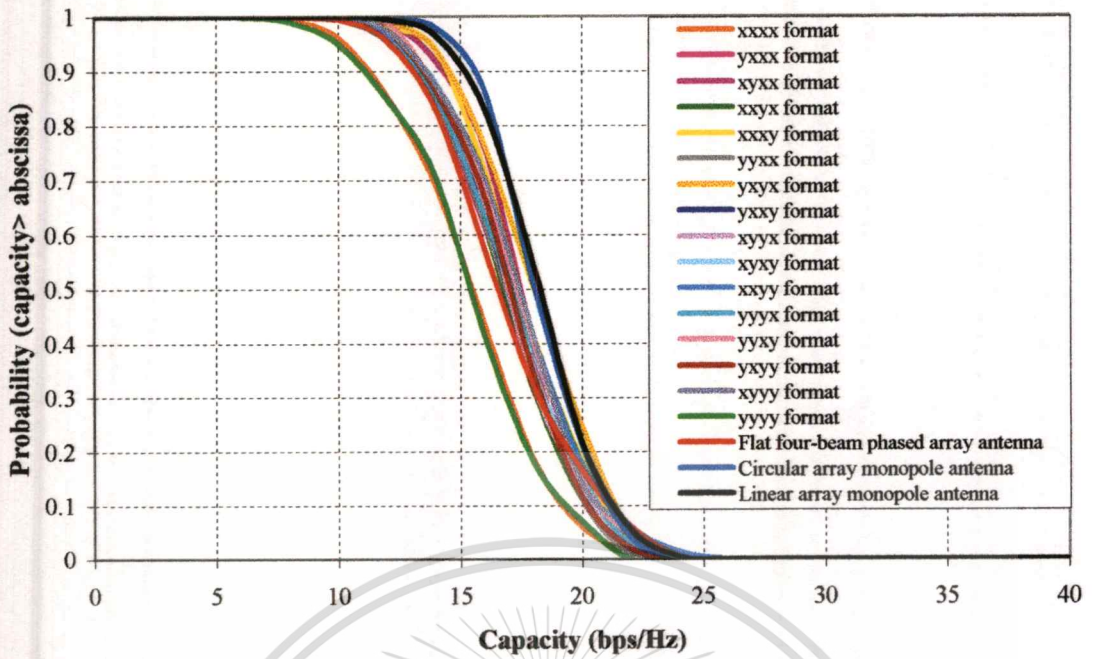


Figure 4.17 The CCDF of MIMO system using phased array antenna of switched-beam elements for all 16 bias formats.

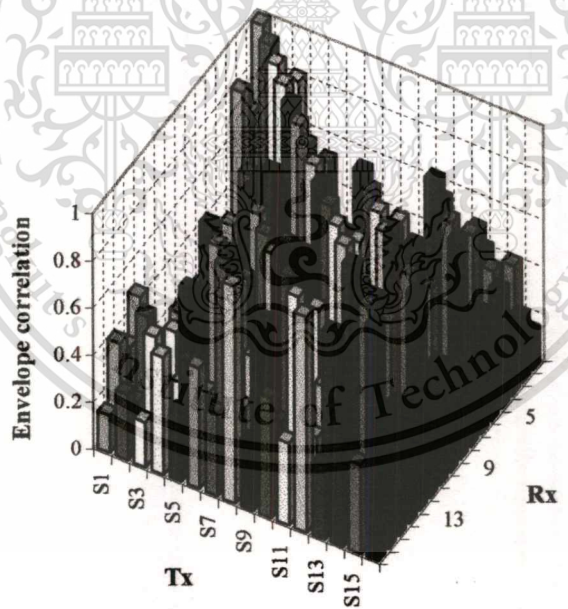


Figure 4.18 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at both transmitting and receiving sides with an average magnitude of envelope correlation of 0.45.

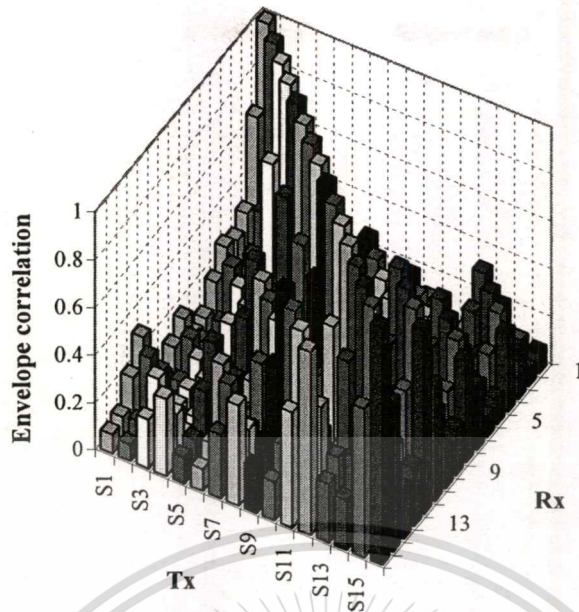


Figure 4.19 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and uniform circular array monopole antennas at receiving side with an average magnitude of envelope correlation of 0.31.

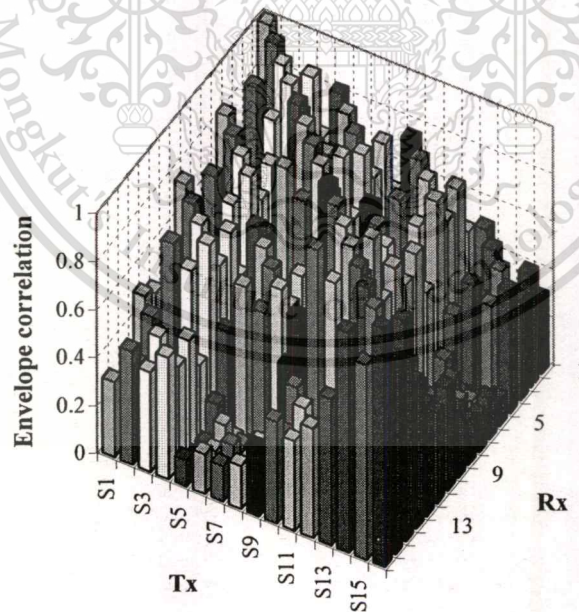


Figure 4.20 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a flat four-beam phased array antenna at receiving side with an average magnitude of envelope correlation of 0.49.

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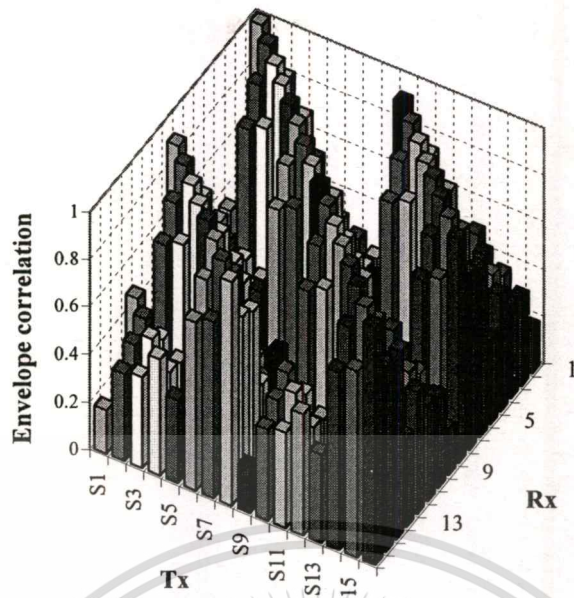


Figure 4.21 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with xxx bias format at receiving side with an average magnitude of envelope correlation of 0.46.

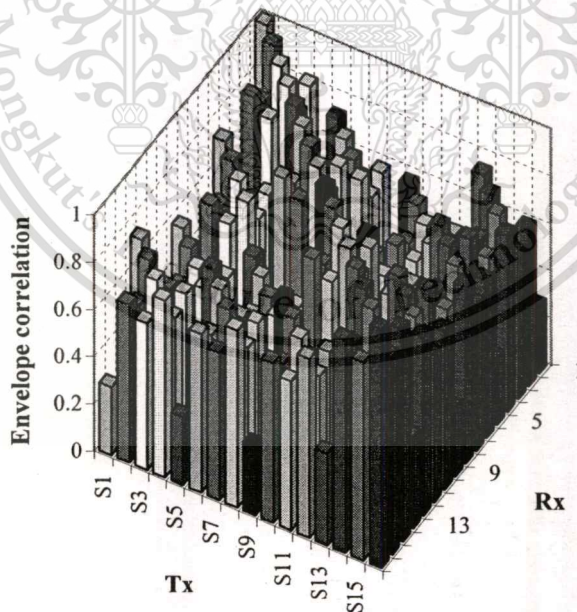


Figure 4.22 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with yxxx bias format at receiving side with an average magnitude of envelope correlation of 0.54.

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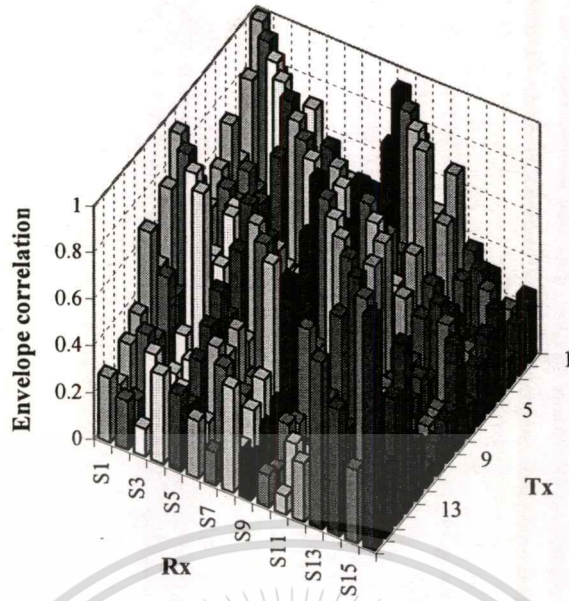


Figure 4.23 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $yxxx$  bias format at receiving side with an average magnitude of envelope correlation of 0.44.

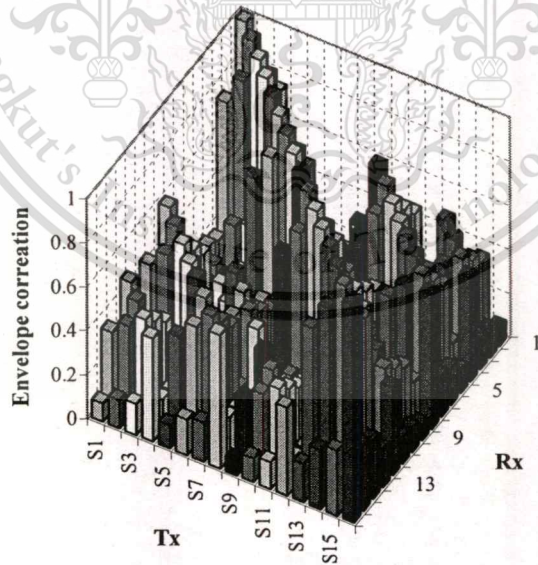


Figure 4.24 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xxyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.35.

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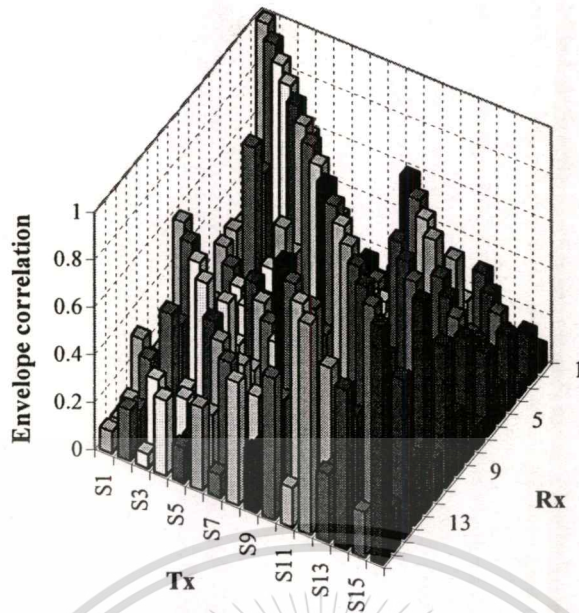


Figure 4.25 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with xxxy bias format at receiving side with an average magnitude of envelope correlation of 0.33.

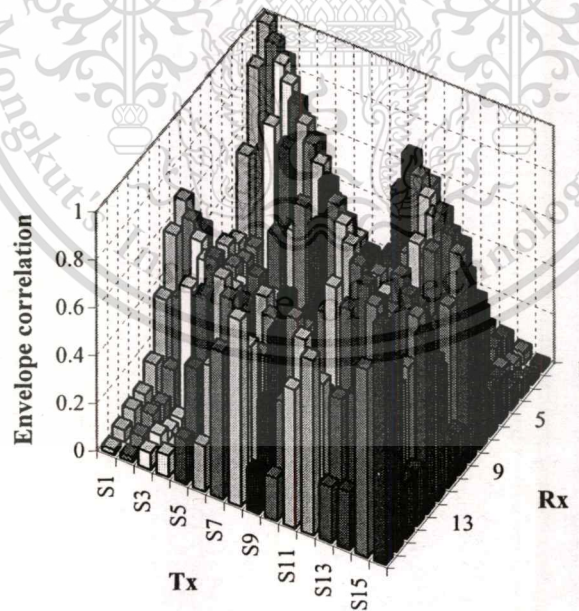


Figure 4.26 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with yyxx bias format at receiving side with an average magnitude of envelope correlation of 0.41.

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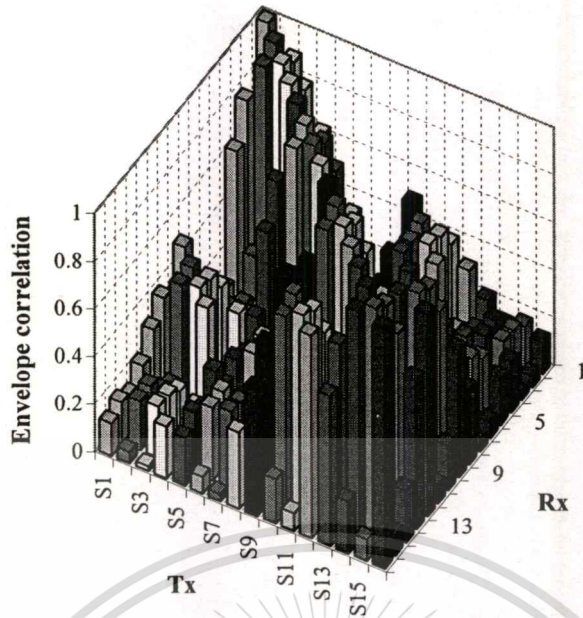


Figure 4.27 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $yxyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.35.

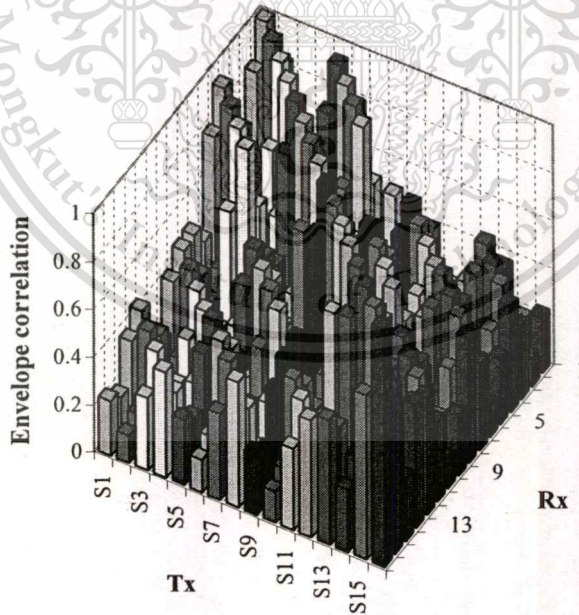


Figure 4.28 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $yxyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.43.

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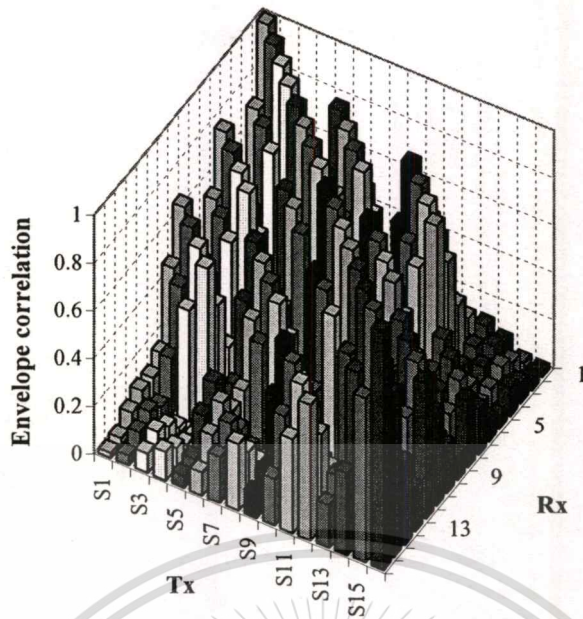


Figure 4.29 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.38.

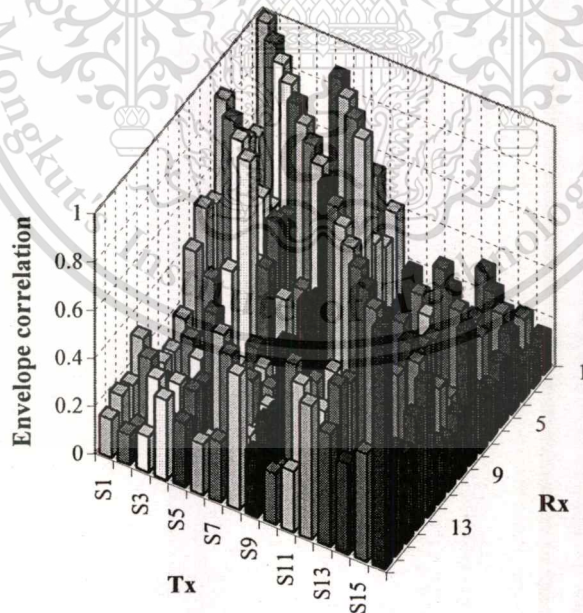


Figure 4.30 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.35.

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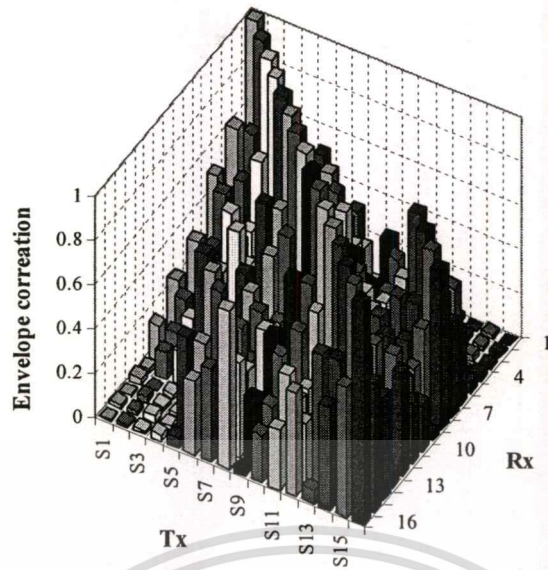


Figure 4.31 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyxy$  bias format at receiving side with an average magnitude of envelope correlation of 0.31.

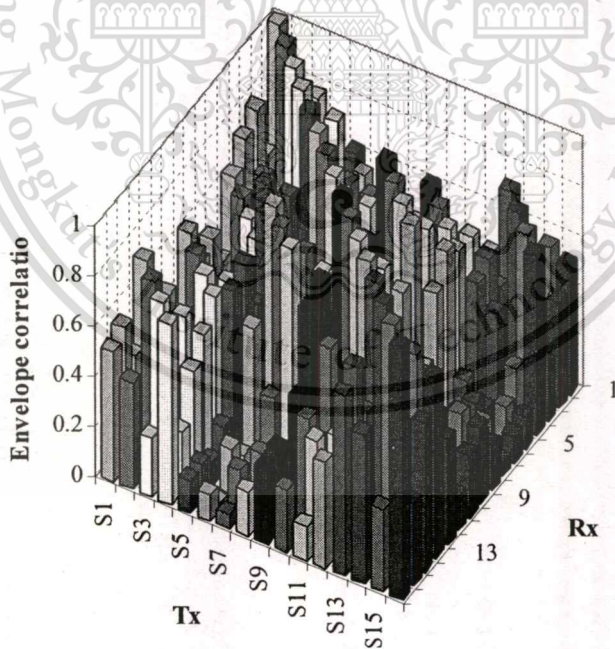


Figure 4.32 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $yyyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.43.

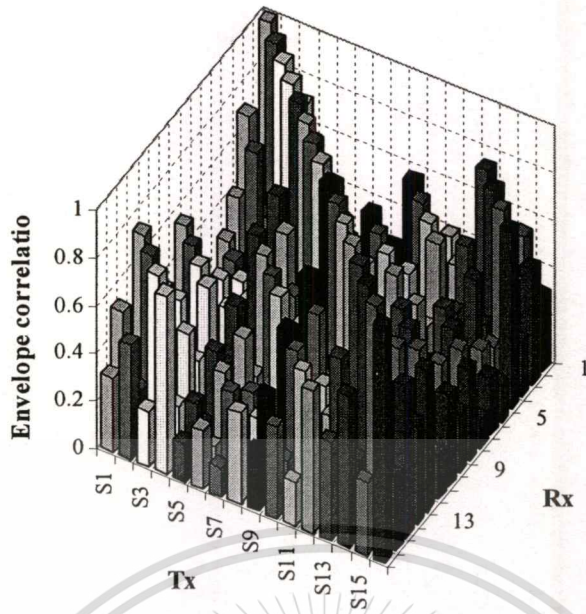


Figure 4.33 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $yxyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.39.

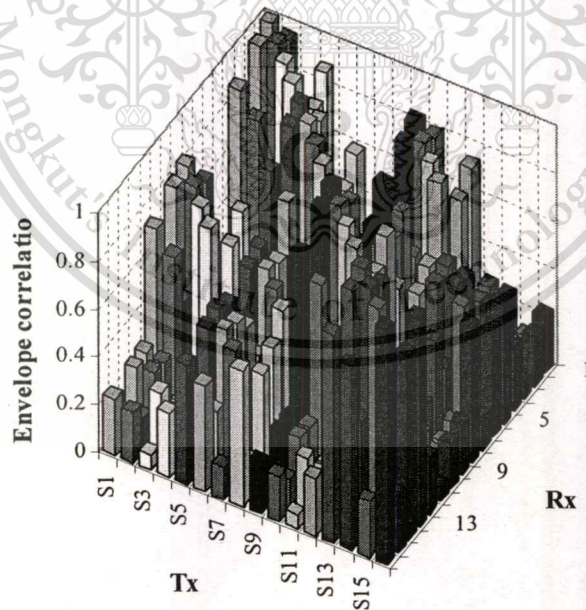


Figure 4.34 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyxy$  bias format at receiving side with an average magnitude of envelope correlation of 0.43.

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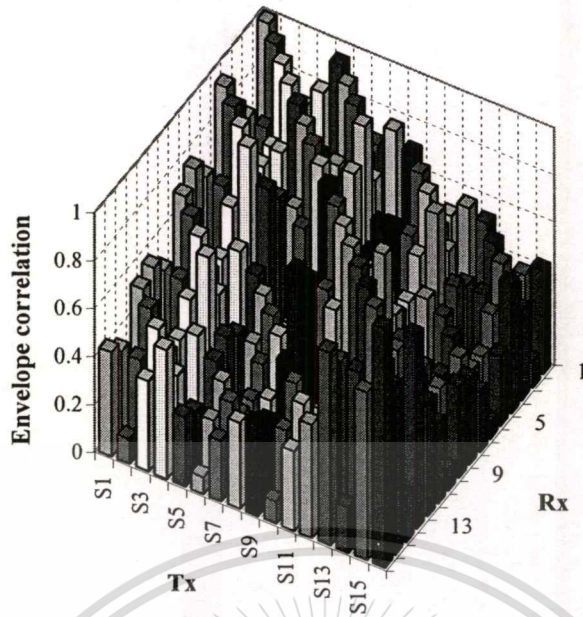


Figure 4.35 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyyy$  bias format at receiving side with an average magnitude of envelope correlation of 0.46.

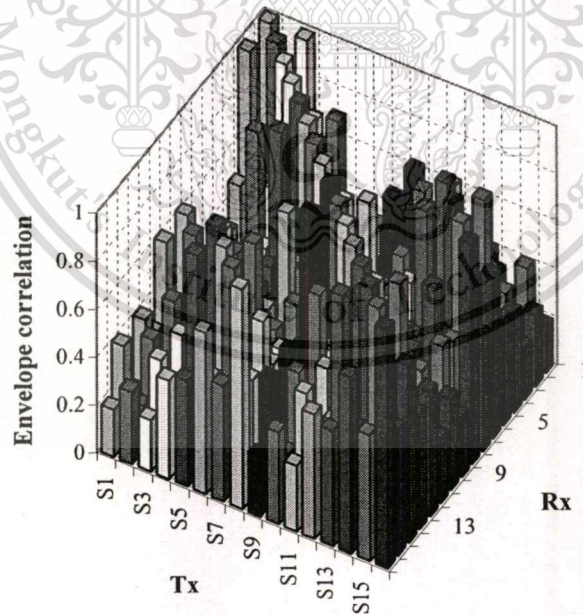


Figure 4.36 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $yyyy$  bias format at receiving side with an average magnitude of envelope correlation of 0.45.

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Finally, a phased array antenna of switched-beam elements at the receiving side is assumed to switch only at the same main beam directions, but difference in 4 bias formats (only xxxx, yxxx, xyxx and xxyx formats). Thus, a  $4 \times 4$  MIMO channel can be given from one main beam direction. Figure 4.37 shows the capacity as a function of SNR. A phased array antenna of switched-beam elements is performed for all four main beam directions and the capacity are compared with the four-element ULA and the four-element UCA of monopole antenna and a flat four-beam phased array antenna. In case of main beam directions at  $135^\circ$ ,  $225^\circ$  and  $315^\circ$ , the channel capacity are higher than those of the ULA and UCA of monopole antenna and flat four-beam phased array antenna due to the switched-beam antenna switches the main beam pointed to the MS antenna. For main beam direction at  $45^\circ$ , the capacity is closed to that of the ULA of monopole antenna. The CCDF of capacity is shown in Figure 4.38. The capacity in this case exceeds 12.5 bps/Hz at 90 % probability and also higher than the previous case.

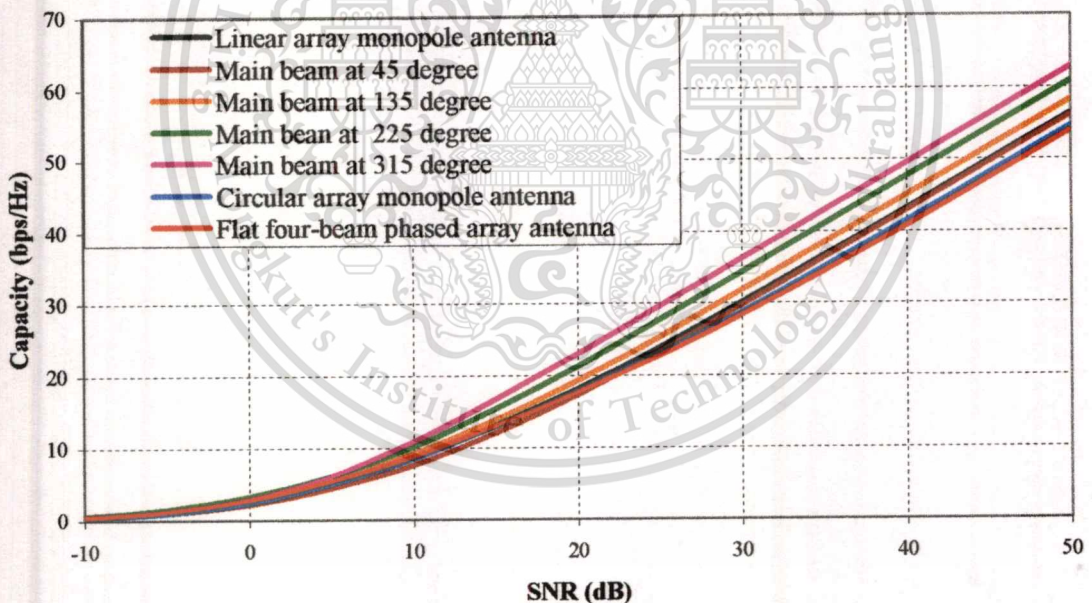
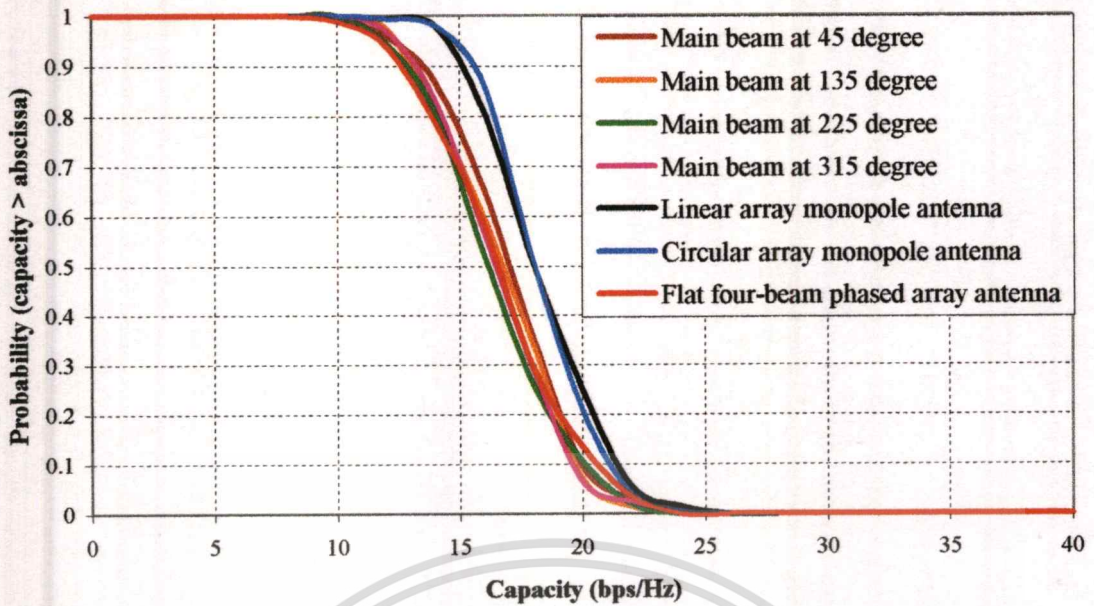


Figure 4.37 Capacity of MIMO system using phased array antenna of switched-beam elements switch to the same main beam direction with four-element transmitting antenna.



**Figure 4.38** The CCDF of MIMO system using phased array antenna of switched-beam elements switch to the same main beam direction with four-element transmitting antenna.

The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO indoor wireless channel by using a phased array antenna of switched-beam elements switches at the same main beam direction at the receiving side are illustrated from Figure 4.39 to Figure 4.42. The average magnitude of envelope correlation between the transmitting and the receiving sides are 0.37, 0.38, 0.58 and 0.31, respectively. The channel characteristics are presented as correlated channel.

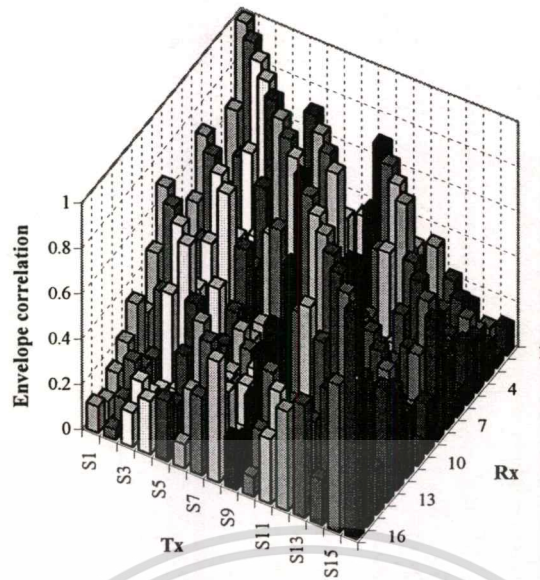


Figure 4.39 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements for main beam direction at  $45^\circ$  at the receiving side with an average magnitude of envelope correlation of 0.37.

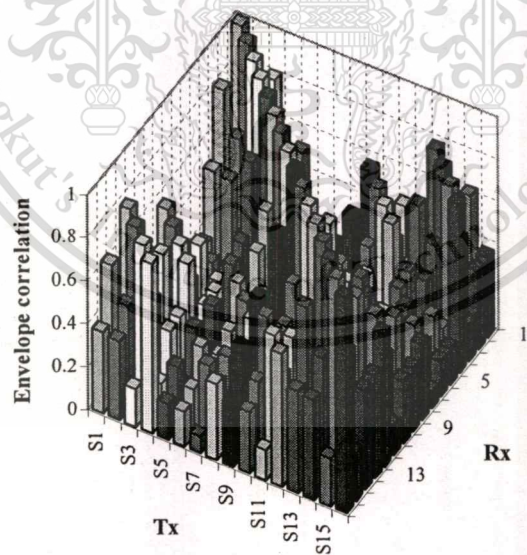
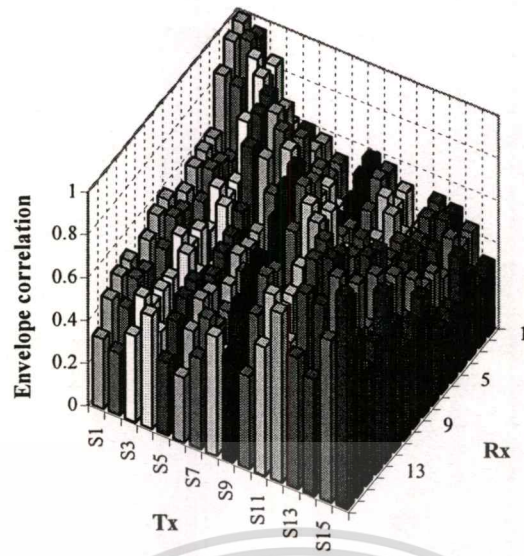


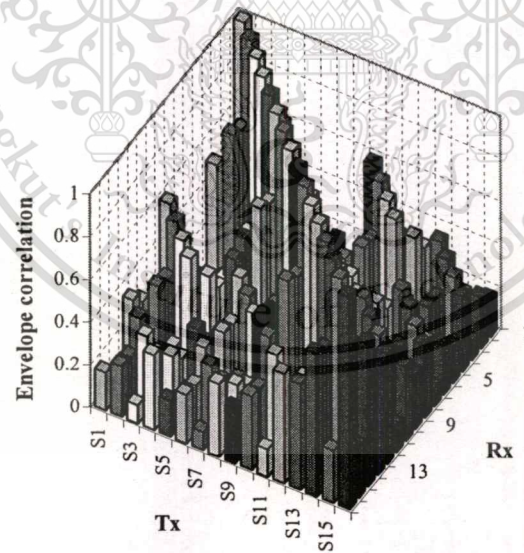
Figure 4.40 The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements for main beam direction at  $135^\circ$  at the receiving side with an average magnitude of envelope correlation of 0.38.

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**Figure 4.41** The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements for main beam direction at  $225^\circ$  at the receiving side with an average magnitude of envelope correlation of 0.58.



**Figure 4.42** The magnitude of the envelope correlation matrix for a  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements for main beam direction at  $315^\circ$  at the receiving side with an average magnitude of envelope correlation of 0.31.

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#### 4.5 Summary

The channel capacity can be improved by using the switched-beam antenna, especially the switched-beam antenna that can provide the large number of radiation patterns. It can be concluded that the more radiation patterns, the more sub-channels, resulting in high feasibility in capacity enhancement. Moreover, when the number of transmitting antennas is increased, the capacity can be improved as well. As a result, the phased array antenna of switched-beam elements can give significant improvement of channel capacity in MIMO system with more compact in size, and cost of multiple receivers used in MIMO system may be reduced since the switched-beam antennas applied herein are single-port structure. The average magnitude of envelope correlation for MIMO systems by using switched-beam antenna is lower than 0.7 and enough to use for an indoor environment.



# CHAPTER 5

## MEASUREMENT OF MIMO INDOOR WIRELESS CHANNELS

### CHANNELS

#### 5.1 Introduction

This chapter presents measurement results of the switched-beam antennas. The measurement campaign was conducted in the Wireless Communication Laboratory, Research Center for Communications and Information Technology (ReCCIT) at King Mongkut's Institute of Technology Ladkrabang (KMITL). At first, the measurement scenario of the Wireless Communication Laboratory is given. Then, the measurement equipments are presented, followed by the measurement process and measurement setup in measurement scenario. Finally, the performances of MIMO system by using switched-beam antennas are given.

#### 5.2 MIMO Channel Measurements

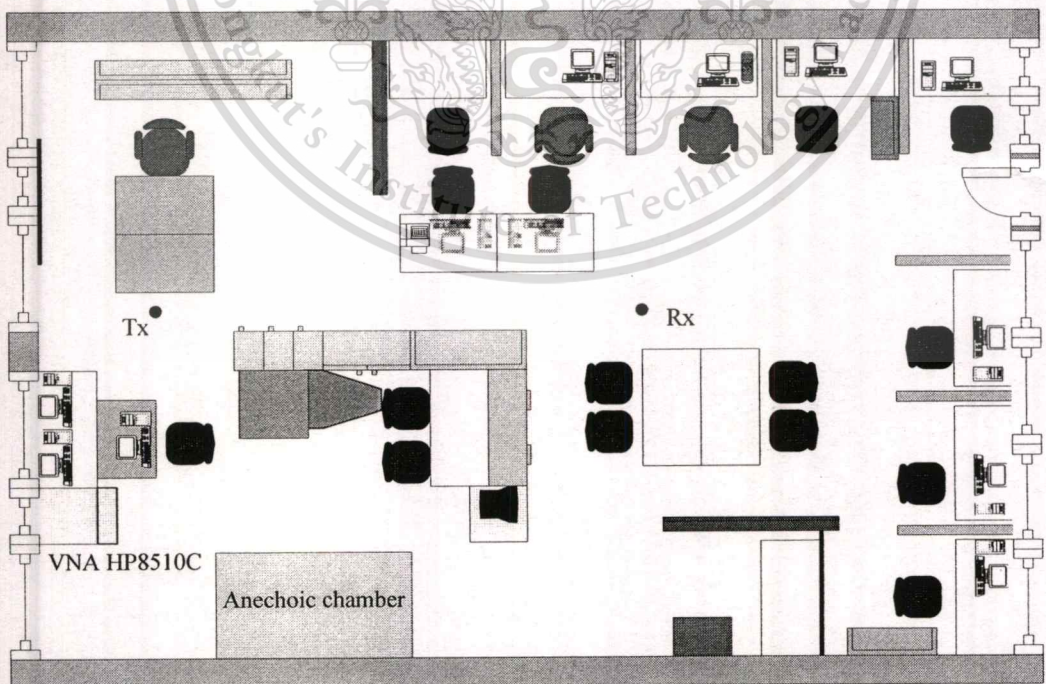


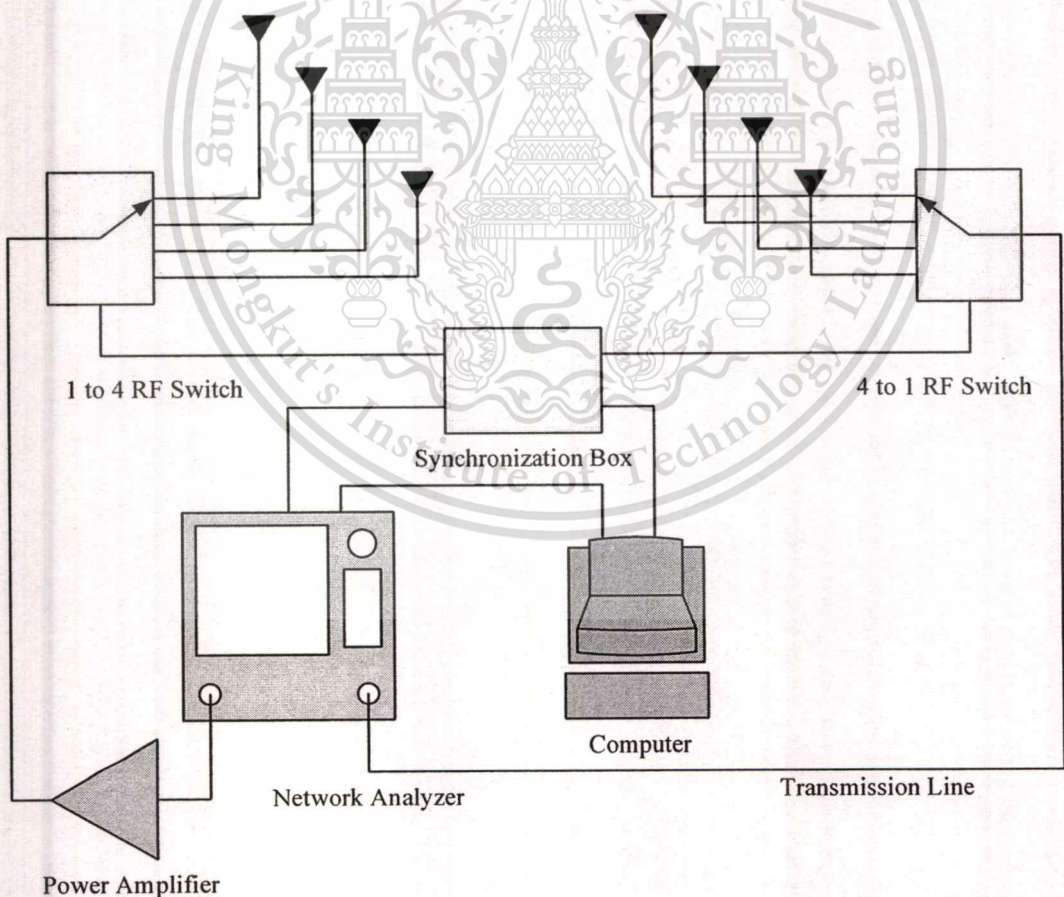
Figure 5.1 Measurement scenario.

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### 5.2.1 Measurement Scenario

The measurement site was performed in the Wireless Communication Laboratory, located on the 10<sup>th</sup> floor of the Kromluangnarathivaj Rajanakarin Building, King Mongkut's Institute of Technology Ladkrabang. Figure 5.1 shows the measurement scenario includes 18 tables, 18 chairs, 13 desktop computers, 2 chambers, 1 locker, 3 bookcases, 1 cabinet and another office equipments. Laboratory dimension is a cube, 11 meter long, 8 meter wide and 2.2 meter high. The transmitting antenna was located on the Tx position the receiving antenna was located on the Rx position. The receiving antenna position was 4 meters separated from side wall and front wall. The transmitting antenna position was 5 meters separated from the receiving antenna. Both the transmitting and receiving antennas were located at a height of 1.5 meters from the floor. The measurement was performed in line of sight (LOS) scenario.



**Figure 5.2** Measurement setup for measuring the channel transfer matrices.

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### 5.2.2 Measurement System

The measurement system was designed to measure the channel transfer matrices of MIMO indoor wireless channels. The vector network analyzer (VNA) HP8510C is effectively used to measure the complex frequency response of the channel at 1.95 GHz. This measurement technique was proposed in [24]. Figure 5.2 shows the measurement system includes 2 sets of linear array of monopole antennas, vector network analyzer HP8510C, power amplifier HP83050A, 1 to 4 RF switch, 4 to 1 RF switch, transmission lines, desktop computer and synchronization box. The pictures of equipment can be shown in Figure 5.3 and in Figure 5.4.

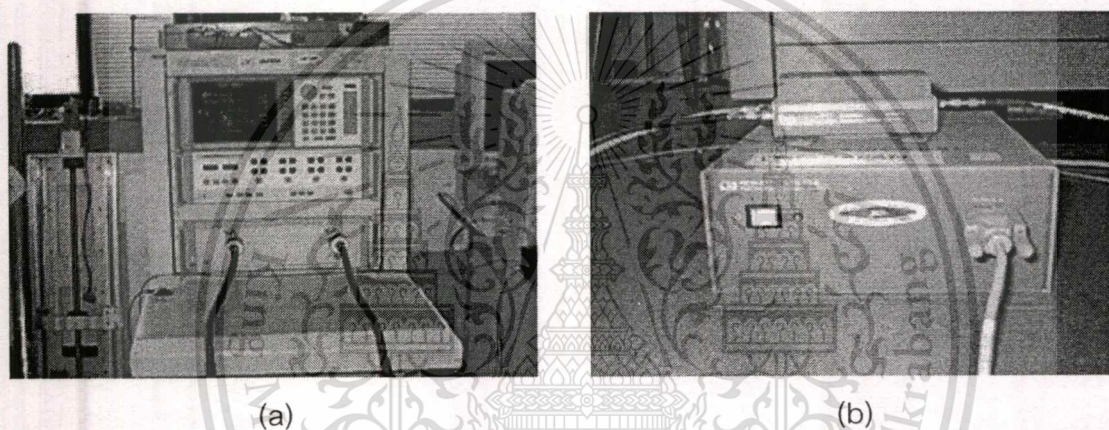


Figure 5.3 Photograph of the equipment (a) vector network analyzer HP8510C (b) power amplifier HP83050A and power supply HP87422A.

### 5.2.3 Measurement Process

The measurements were carried out using the VNA HP8510C by using single frequency at 1.95 GHz. The calibration process of experiment has been done by using true calibration response with 10 dBm transmitting power. Firstly, a  $4 \times 4$  MIMO channel was measured. The transmitting antenna using four-element uniform linear array of monopole antennas with inter element spacing  $\lambda/2$  was placed at the Tx position (see Figure 5.1) and the receiving antenna using four-element uniform linear array of monopole antennas with inter element spacing  $\lambda/2$  was placed at the Rx position. The distance between the transmitter and the receiver was five meters. A VNA HP8510C was used to measure the channel transmission coefficient (by using S21) for all 16 channels

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using synchronization box. The RF switches were controlled by using synchronization box, and the sets of data were stored in desktop computer. The HP83050A power amplifier with power gain of 20 dB was used for increasing the transmitting power to be higher than noise level. The measurements were performed 200 times for calculating average channel matrix and plot the CCDF. Then, the receiving antenna was replaced by using switched-beam antennas and followed by the same measurement process. Finally, the receiving antenna was replaced by using four-element uniform circular array of monopole antennas.

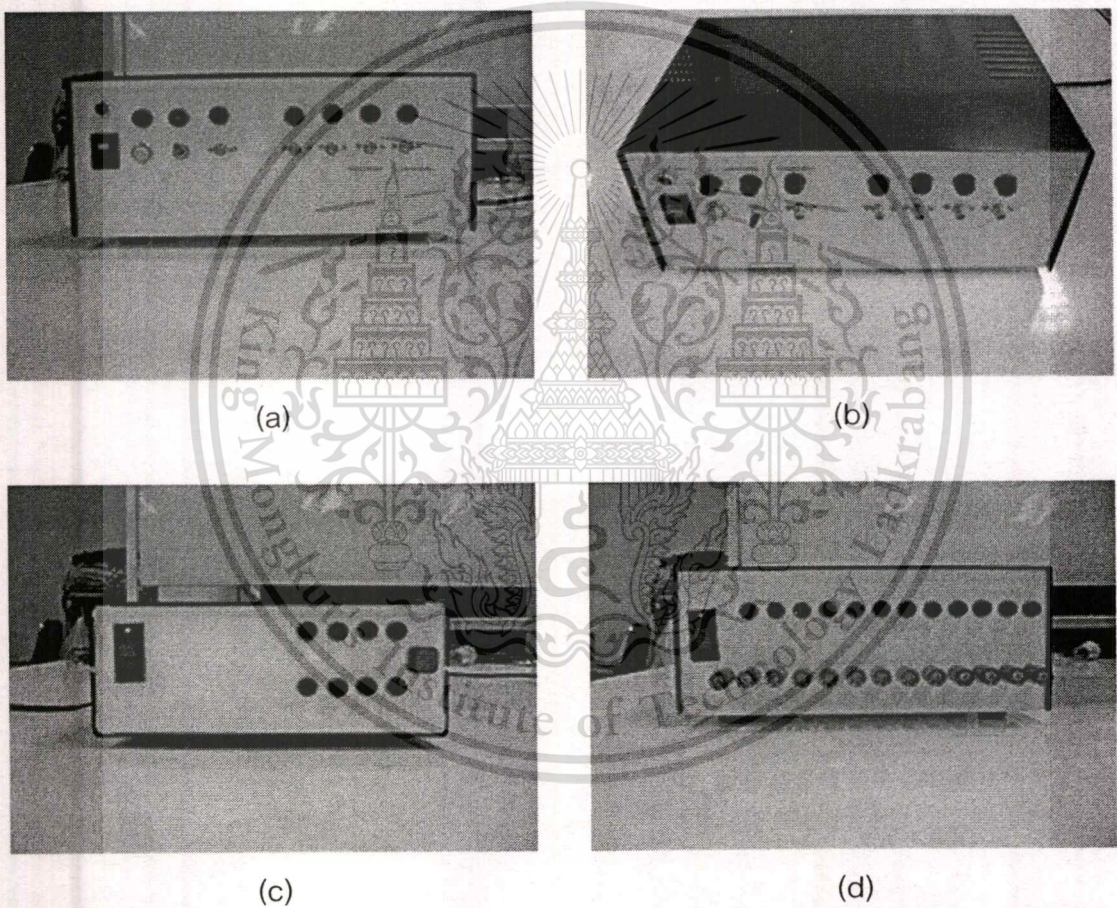


Figure 5.4 Photograph of the equipment continued (a) 1 to 4 RF switch (b) 4 to 1 RF switch (c) control box (d) power supply for switched-beam antennas.

For a  $2 \times 2$  MIMO system, the measured data was selected from a  $4 \times 4$  MIMO system. Figure 5.5 to Figure 5.9 show photograph of the measurement setup of the MIMO system.

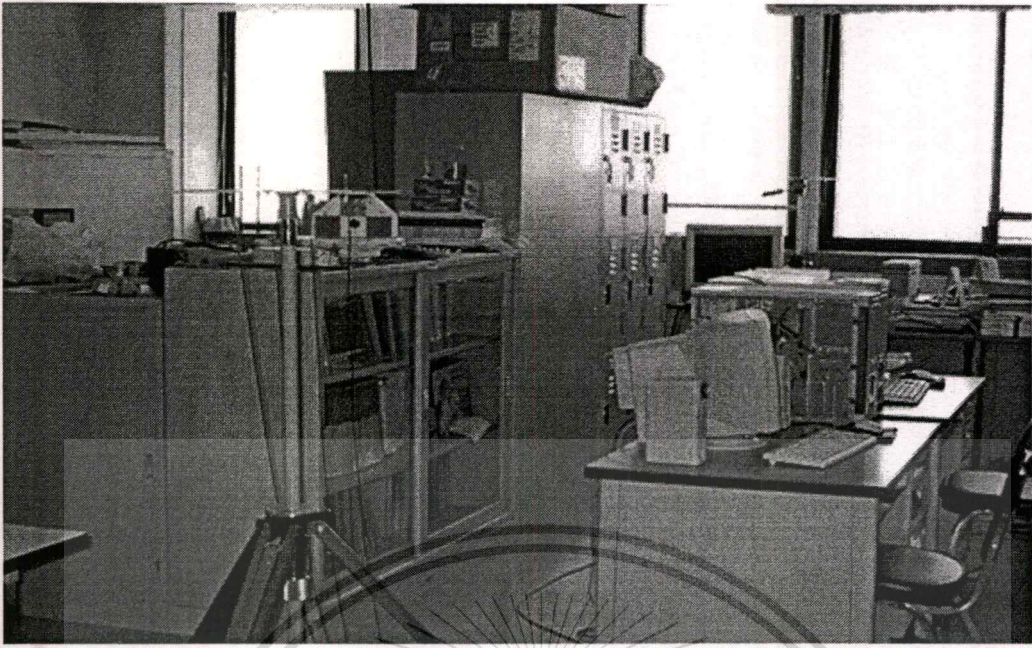


Figure 5.5 Measurement system of MIMO system with four-element ULA of monopole antennas at both the transmitter and the receiver sides.

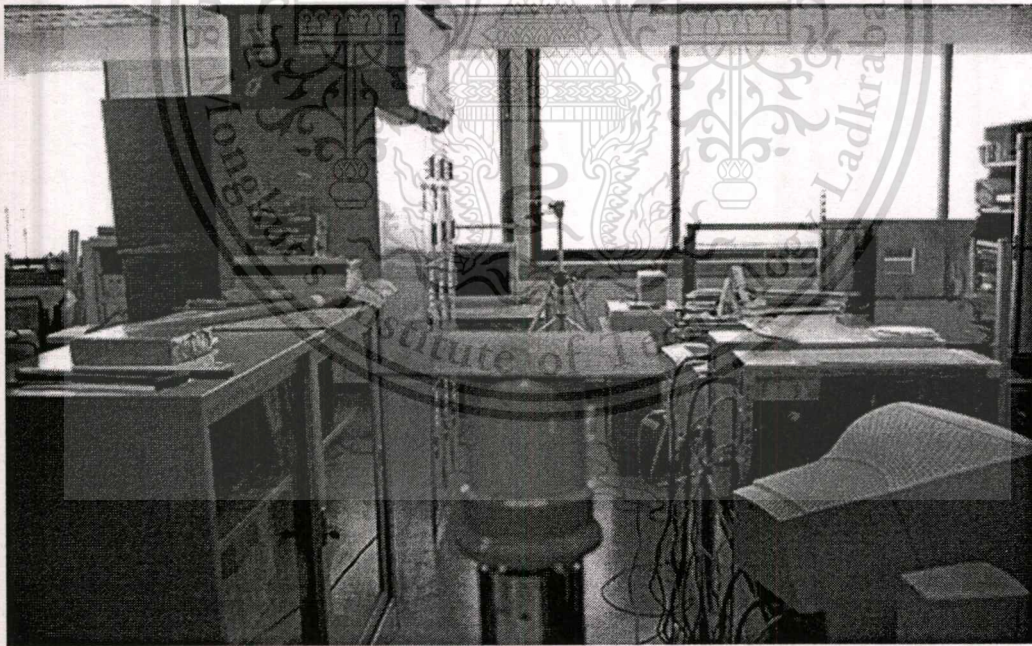


Figure 5.6 Measurement system of MIMO system with four-element ULA of monopole antennas at the transmitter side and a switched-beam single patch antenna at the receiver side.

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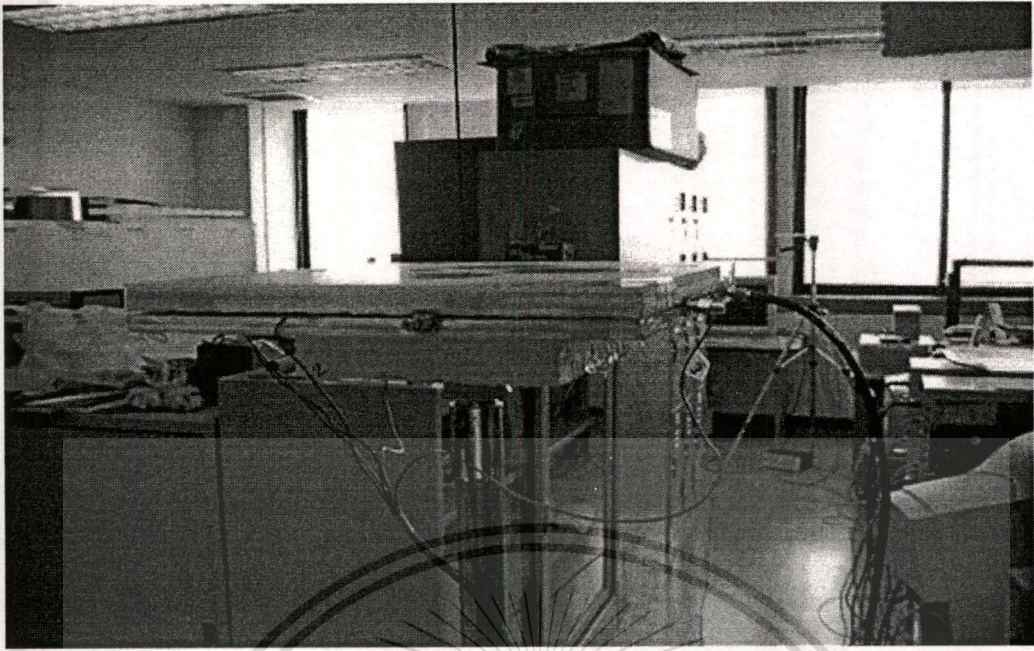


Figure 5.7 Measurement system of MIMO system with four-element ULA of monopole antennas at the transmitter side and a flat four-beam phased array antenna at the receiver side.



Figure 5.8 Measurement system of MIMO system with four-element ULA of monopole antennas at the transmitter side and a phased array antenna of switched-beam elements at the receiver side.

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**Figure 5.9** Measurement system of MIMO system with four-element ULA of monopole antennas at the transmitter side and four-element UCA of monopole antennas at the receiver side.

The measured data was compensated the effects of mutual coupling by using the method proposed in [25]. The coupling matrix is a simple approach by which the channels is multiplied by the coupling matrices  $C_T$  and  $C_R$  for transmit and receive side, respectively. New channel matrix with mutual coupling can be written as

$$H_C = C_T H C_R \quad (5.1)$$

where  $H_C$  denote for the new channel matrix. Using circuit theory, it is shown that the mutual coupling matrix can be written as

$$C = (Z_T + Z_A)(Z + Z_T I)^{-1} \quad (5.2)$$

where  $Z_A$  is the antenna impedance,  $Z_T$  is the load impedance of each element, fixed to 50 ohms, and  $Z$  is the mutual impedance matrix.

### 5.3 Measurement Results

At first, the measurement system comprising two transmitting antennas and multiple receiving antennas is considered. The channel capacity of this system using switched-beam antenna is computed by applying the switched-beam antenna as the

multiple receiving antennas and the monopole antenna array as the transmitting antennas. Figure 5.10 shows the measurement channel capacity as function of SNR received at the Rx antennas. For illustrative purpose, a 20 dB SNR is used. The capacities increase almost linearly with increase in SNR. In case of two-element transmitting antenna, the channel capacities for two monopole antennas, the switched-beam single patch antenna, the flat four-beam phased array antenna, the phased array antenna of switched-beam elements with xxxx and yyyy formats, four-element UCA of monopole antennas and four-element ULA of monopole antennas are 12.87, 8.98, 12.89, 11.55, 12.72, 12.90 and 13.92 bps/Hz, respectively. In case of single antenna system the capacity only 6.66 bps/Hz. Figure 5.11 shows the case of four-element transmitting antenna, the channel capacities are illustrated in Table 5.1. The capacities of the phased array antenna of switched-beam elements varies from 8.08 to 17.24 bps/Hz, some bias formats such as yxyx the capacity is lower than switched-beam single patch antenna. For the flat four-beam phased array antennas the channel capacity is higher than other antennas. Figure 5.12 shows the capacities of the phased array antenna of switched-beam elements when switching at the same main beam direction, only xxxx, yxxx, xyxx and xxyx formats were performed in these measurements. The capacities for main beam direction at 45°, 135°, 225°, and 315° are 19.67, 19.00, 19.52 and 12.819 bps/Hz, respectively. The capacities are almost closed to four-element UCA and ULA of monopole antennas. However, the flat four-beam phased array antenna can give higher capacity than other antennas.

The CCDF of the measured capacity of MIMO system using switched-beam antenna with two-element transmitting antenna and four-element transmitting antenna are plotted in Figure 5.13 and in Figure 5.14, respectively, at an SNR of 20 dB. With two-element transmitting antenna, two monopole antennas has the capacity exceeds 11.40 bps/Hz at 90 % probability. The switched-beam single patch antenna has the capacity exceeds 7.20 bps/Hz at 90 % probability. The flat four-beam phased array antenna has the capacity exceeds 11.30 bps/Hz and the phased array antenna of switched-beam elements with xxxx format has the capacity exceeds 10.20 bps/Hz, respectively, at 90 % probability. In case of four-element transmitting antenna for a 4 × 4 MIMO system, the CCDF of capacity shows that the performance of the flat four-beam phased array

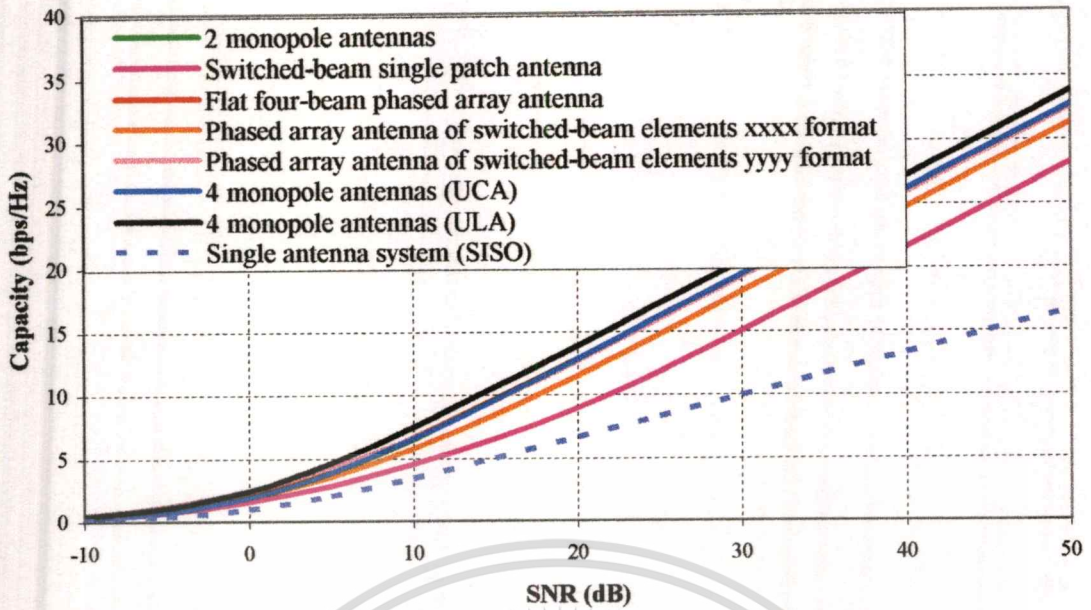


Figure 5.10 Capacity of experimental MIMO system using two-element of monopole antennas as the transmitting antennas.

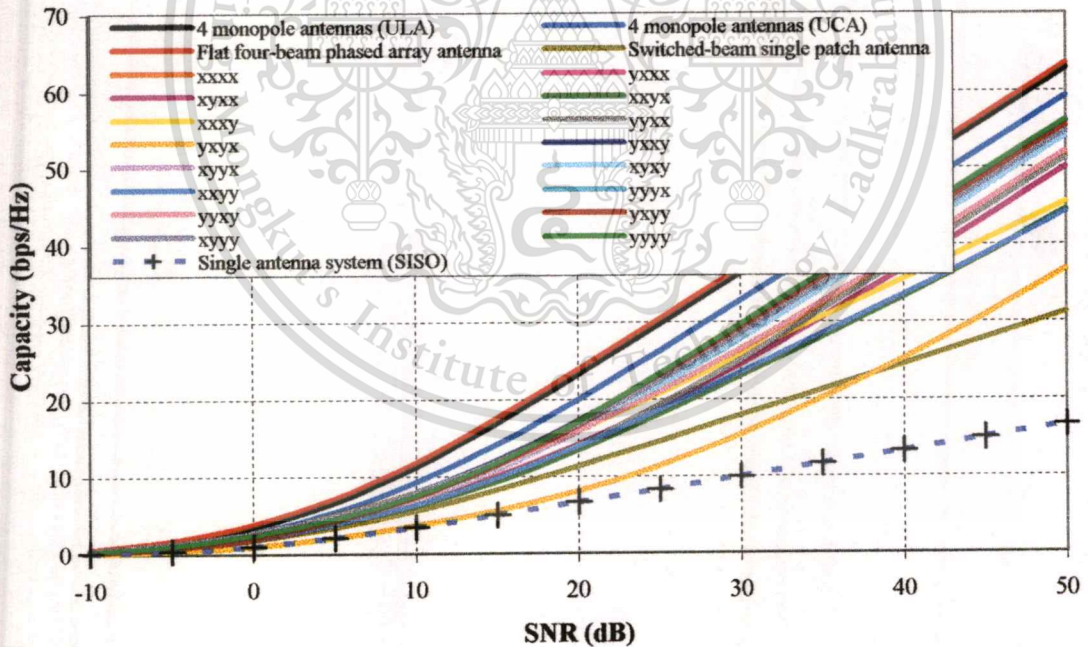


Figure 5.11 Capacity of experimental MIMO system using four-element of monopole antennas as the transmitting antennas.

antenna is greater than the phased array antenna of switched-beam elements, four-element UCA of monopole antennas with the capacity more than 19.80 bps/Hz, whereas the capacities of four-element UCA and ULA of monopole antennas are more than 18.20 and 20.80 bps/Hz, respectively, at 90 % probability. For the phased array antenna of switched-beam elements with 16 bias formats the capacities exceed 12.80 bps/Hz. In case of phased array antenna of switched-beam elements, when switch at the same main beam direction the capacities are more than 13.50 bps/Hz, see Figure 5.15.

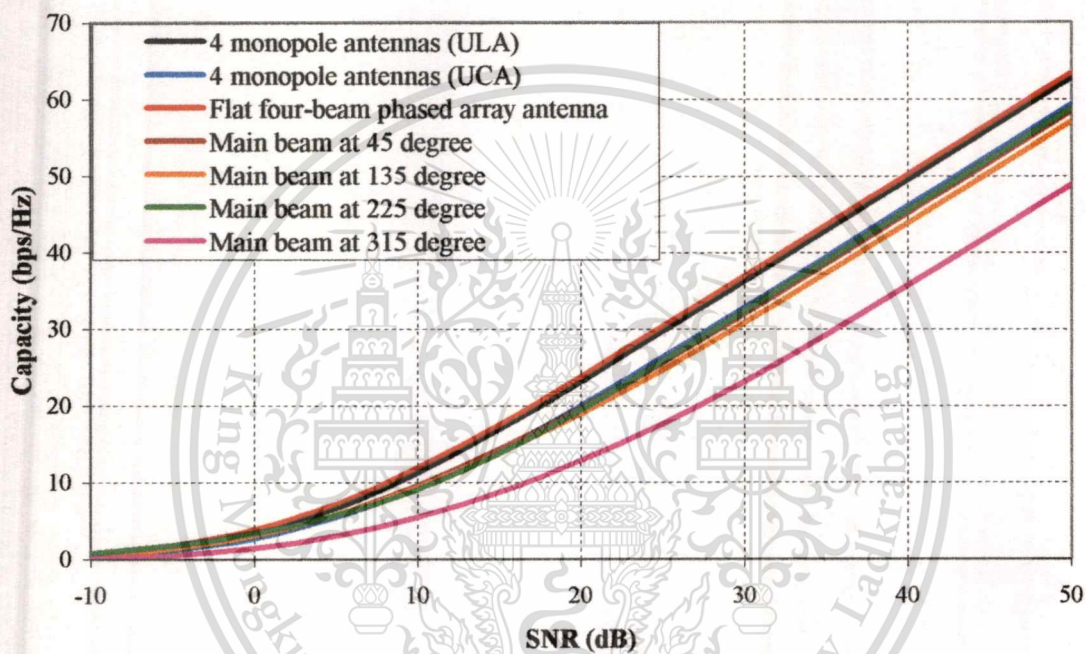


Figure 5.12 Capacity of experimental MIMO system using four-element of monopole antennas as the transmitting antennas and a phased array antenna of switched-beam elements switching in the same main beam direction but difference null patterns.

The correlation property for a  $2 \times 2$  MIMO system are illustrated 5.16 and in Figure 5.17. For a  $2 \times 2$  MIMO system, the magnitude correlation presents the channel as fully correlated channel.

**Table 5.1** Channel capacities of four-element transmitting antennas with 20 dB SNR.

Antenna Configuration	Channel Capacity (bps/Hz)
Switched-beam elements xxxx	16.03
Switched-beam elements yxxx	17.12
Switched-beam elements xyxx	14.21
Switched-beam elements xxyx	13.46
Switched-beam elements xxxy	15.89
Switched-beam elements yyxx	14.04
Switched-beam elements yxyx	8.08
Switched-beam elements yxyx	17.24
Switched-beam elements xyxx	15.87
Switched-beam elements xyxy	15.97
Switched-beam elements xxyy	13.88
Switched-beam elements yyyx	16.79
Switched-beam elements yyxy	15.88
Switched-beam elements yxyy	16.64
Switched-beam elements xyyy	16.79
Switched-beam elements yyyy	17.12
Switched-beam single patch	11.33
Flat four-beam	23.78
4 elements UCA	19.98
4 elements ULA	23.21

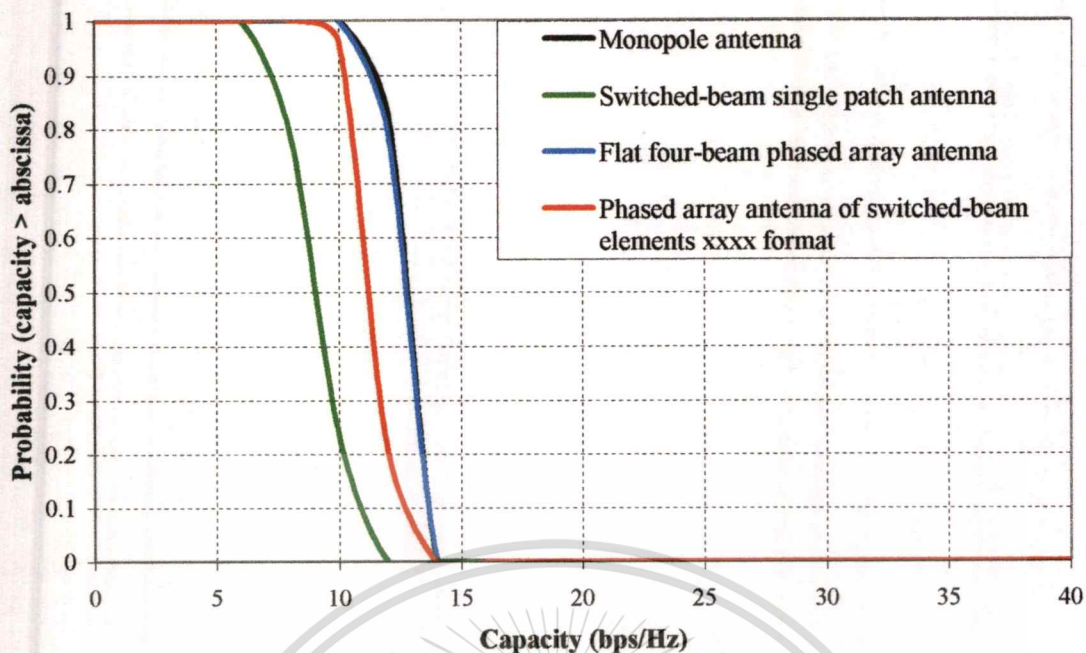


Figure 5.13 CCDF of MIMO system using switched-beam antenna with two-element transmitting antenna based on measured data.

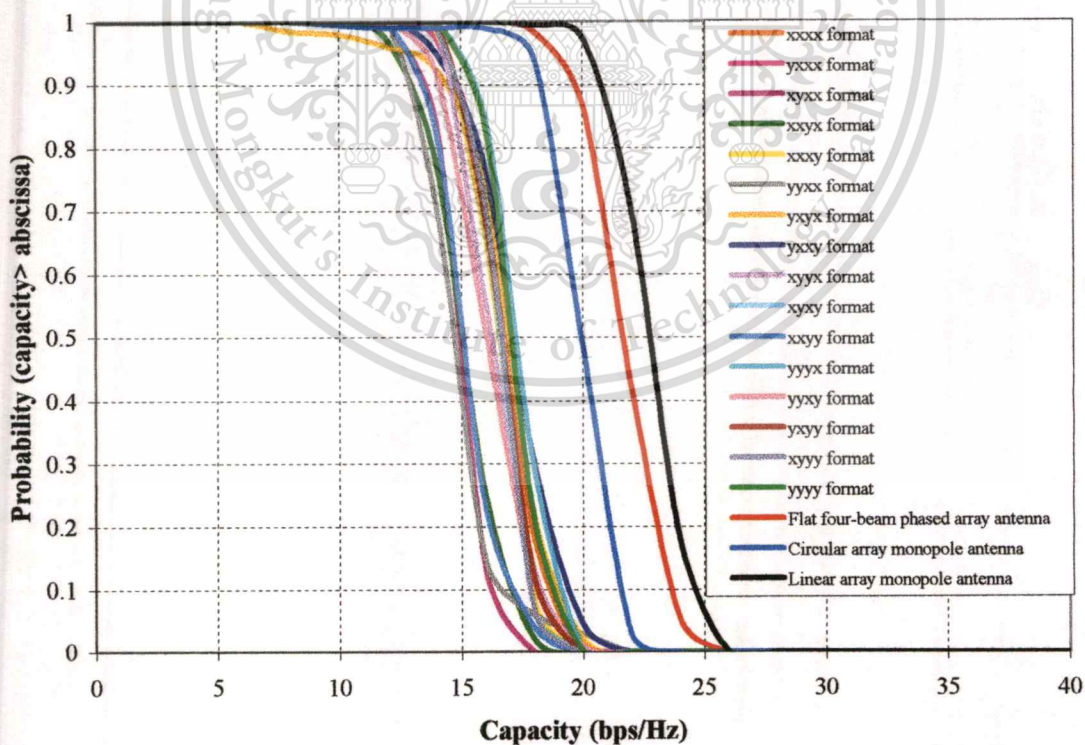


Figure 5.14 CCDF of MIMO system using switched-beam antenna with four-element transmitting antenna based on measured data.

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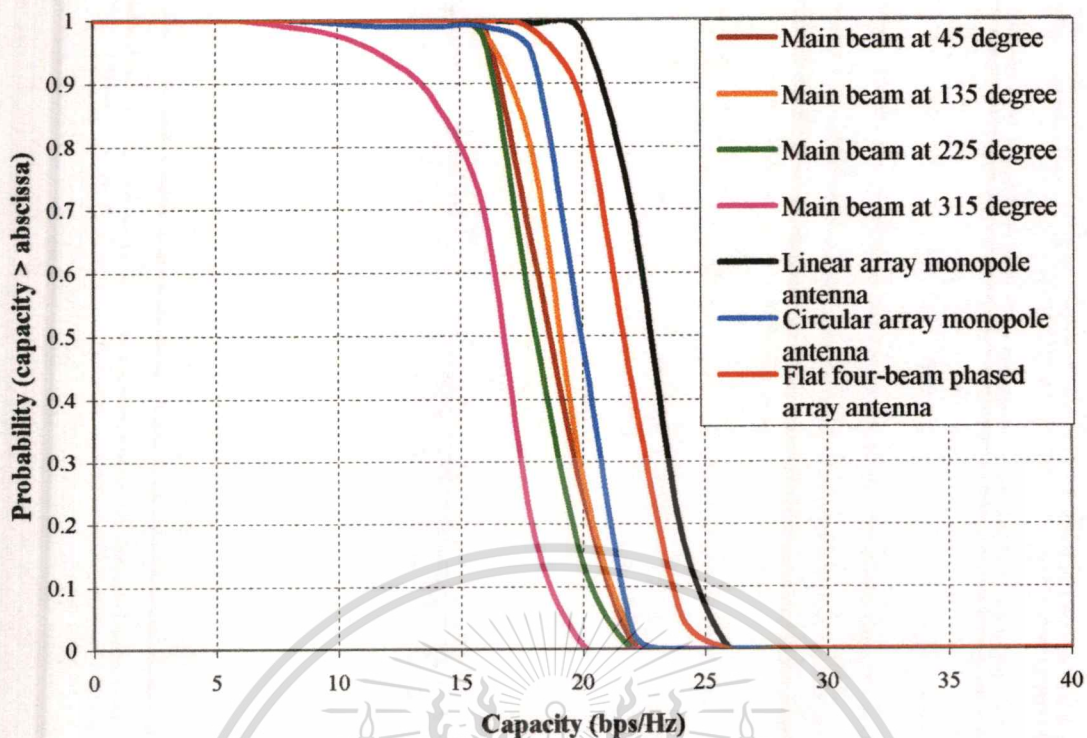


Figure 5.15 CCDF of MIMO system using a phased array antenna of switched-beam elements switch at the same main beam direction with four-element transmitting antenna based on measured data.

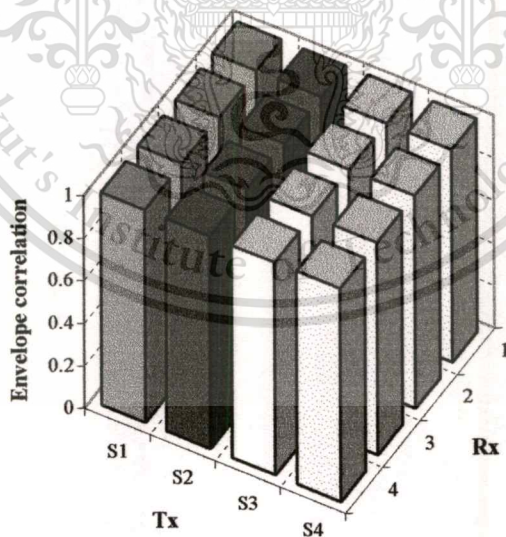
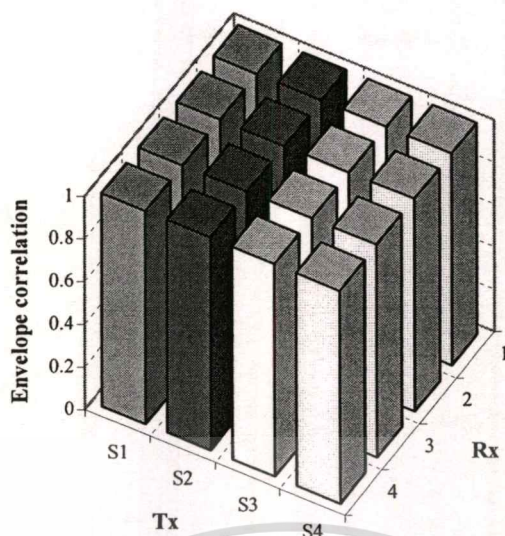
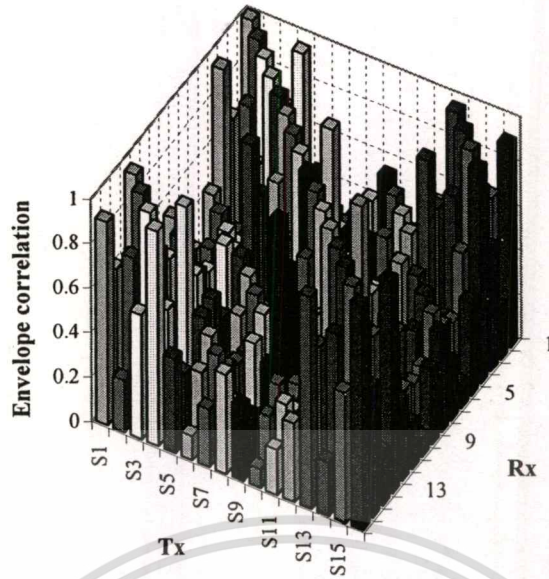


Figure 5.16 Magnitude of the envelope correlation matrix for a measured  $2 \times 2$  MIMO system using the uniform linear array monopole antennas at both the transmitting and the receiving sides.

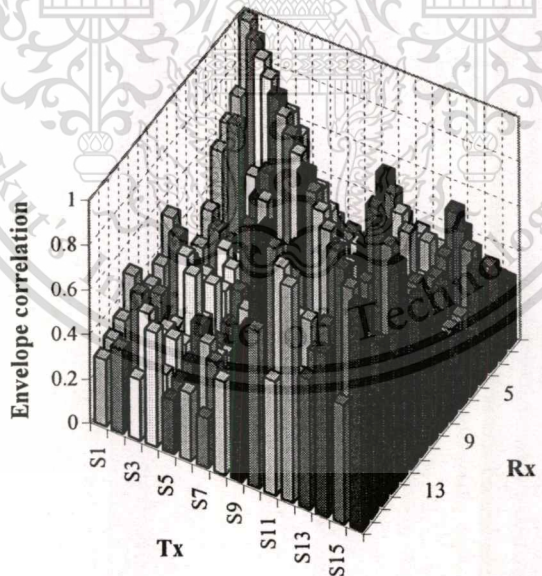


**Figure 5.17** Magnitude of the envelope correlation matrix for a measured  $2 \times 2$  MIMO system using the uniform linear array monopole antennas at the transmitting side and a switched-beam single patch antenna at the receiving side.

For a  $4 \times 4$  MIMO system, the magnitudes of envelope correlation are illustrated in Figure 5.18 to Figure 5.40. Each figure shows the magnitude of envelope correlation between the transmitter and the receiver of the MIMO wireless channels. Comparing the magnitude of envelope correlation between four-element ULA of monopole antennas, four-element UCA of monopole antennas and flat four-beam phased array antenna, we found that the flat four-beam phased array can give lower envelope correlation than both monopole arrays with the average magnitude of envelope correlation of 0.37, leading to higher capacity than those antennas. For a phased array antenna of switched-beam elements the magnitude of envelope correlation are different in each bias formats and the average magnitude of envelope correlation varies from 0.36 to 0.51. Some bias formats, the envelope correlation is lower than the flat four-beam phased array antenna, some bias formats the envelope correlation higher than flat four-beam phased array antenna. However, the spatial envelope correlation of the measured data has shown that the  $4 \times 4$  MIMO indoor wireless system using switched-beam antennas at the receiving side presents as correlated channel.



**Figure 5.18** Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at both transmitting and receiving sides with an average magnitude of envelope correlation of 0.46



**Figure 5.19** Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and uniform circular array monopole antennas at receiving side with an average magnitude of envelope correlation of 0.44.

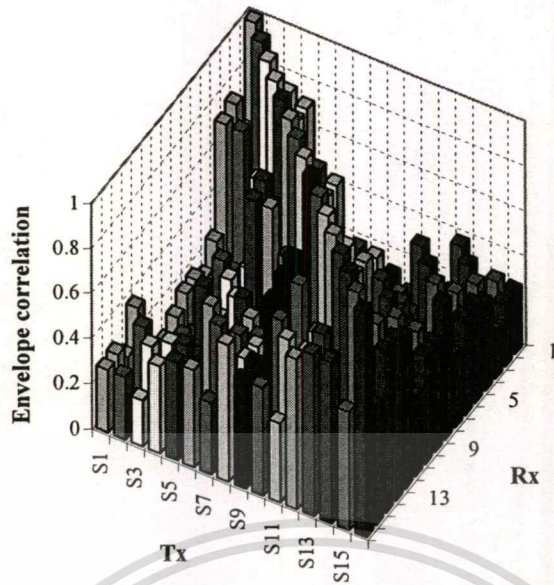


Figure 5.20 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a flat four-beam phased array antenna at receiving side with an average magnitude of envelope correlation of 0.37.

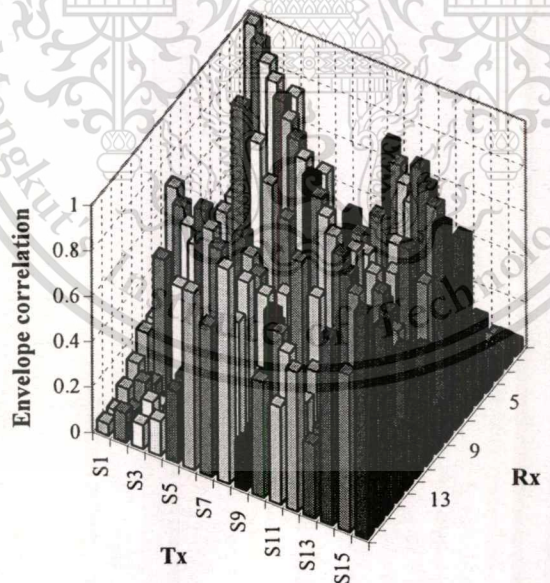


Figure 5.21 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with xxx bias format at receiving side with an average magnitude of envelope correlation of 0.44.

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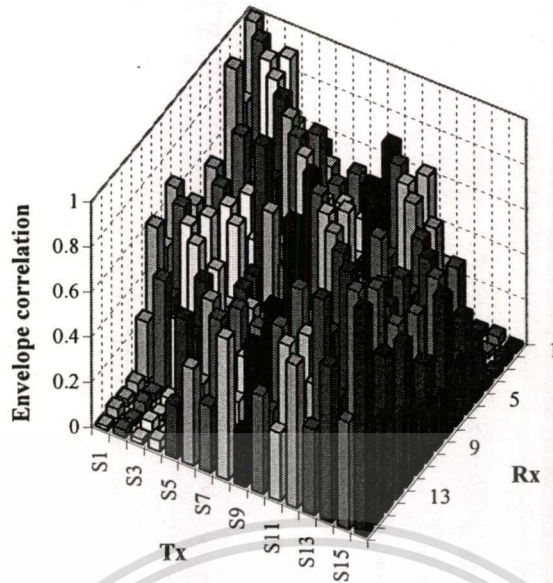


Figure 5.22 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with yxxx bias format at receiving side with an average magnitude of envelope correlation of 0.44.

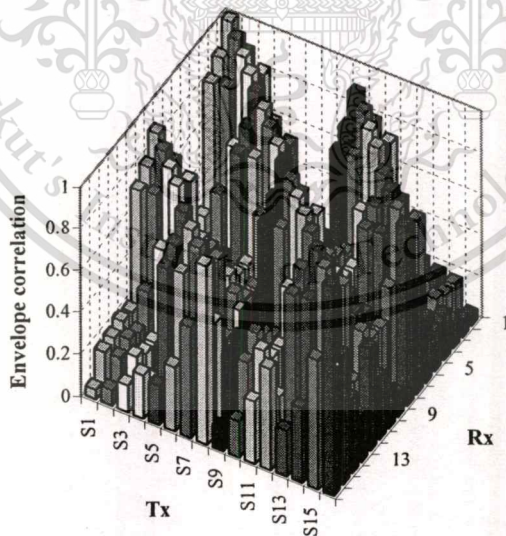
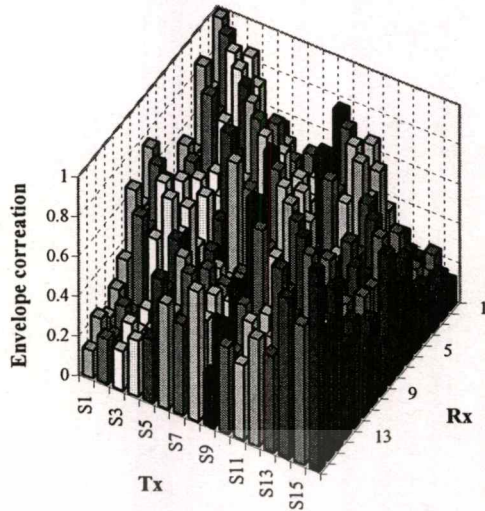


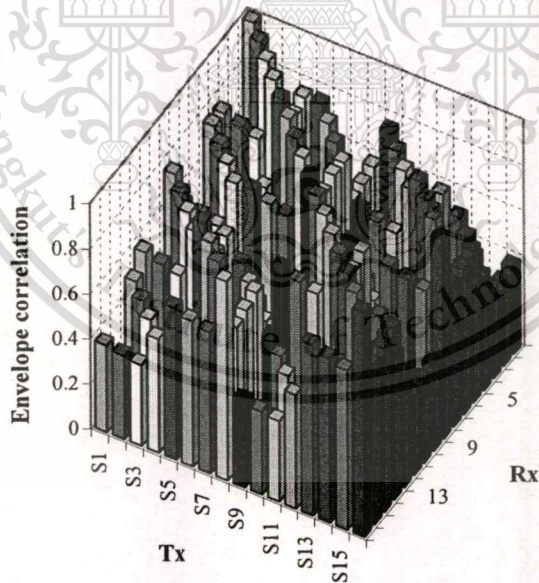
Figure 5.23 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with xyxx bias format at receiving side with an average magnitude of envelope correlation of 0.45.

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**Figure 5.24** Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.51.



**Figure 5.25** Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xxxy$  bias format at receiving side with an average magnitude of envelope correlation of 0.52.

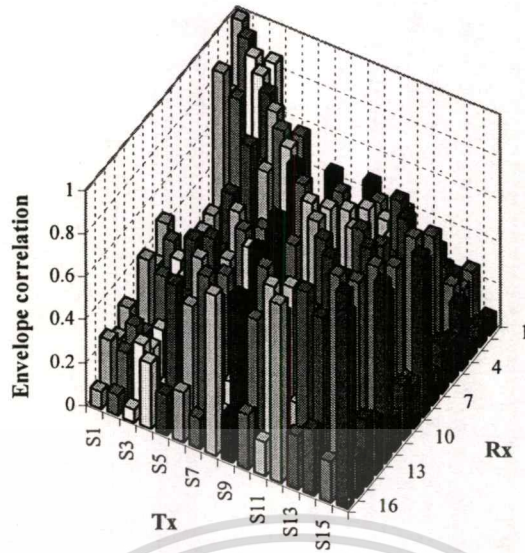


Figure 5.26 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $yyxx$  bias format at receiving side with an average magnitude of envelope correlation of 0.42.

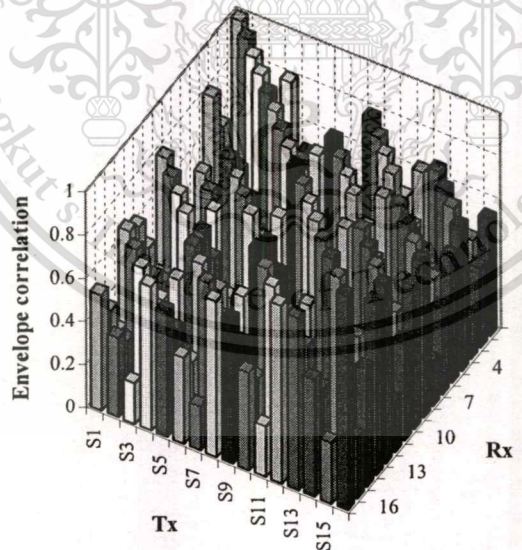


Figure 5.27 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.51.

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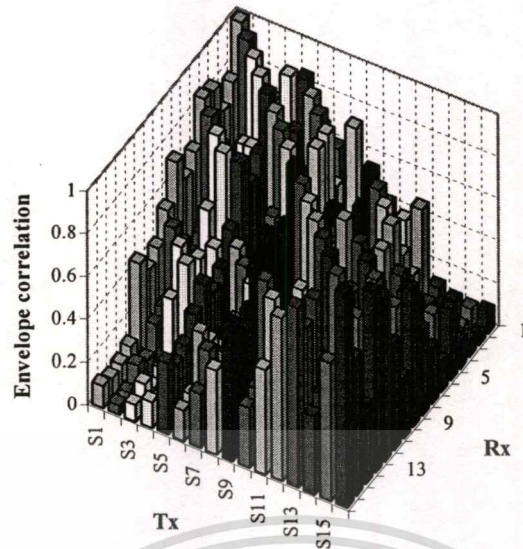


Figure 5.28 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $yxyx$  bias format at receiving side with an average magnitude of envelope correlation of 0.47.

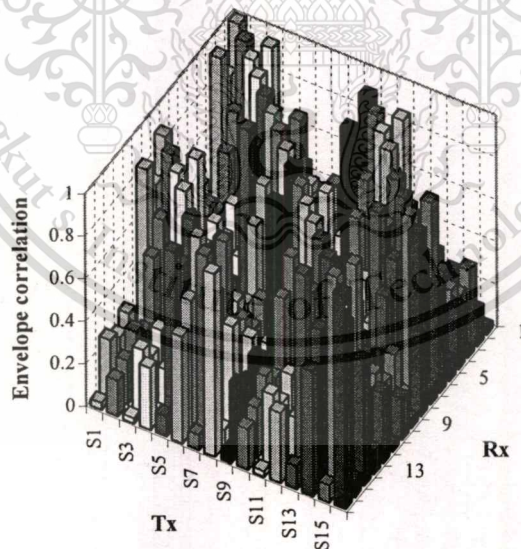
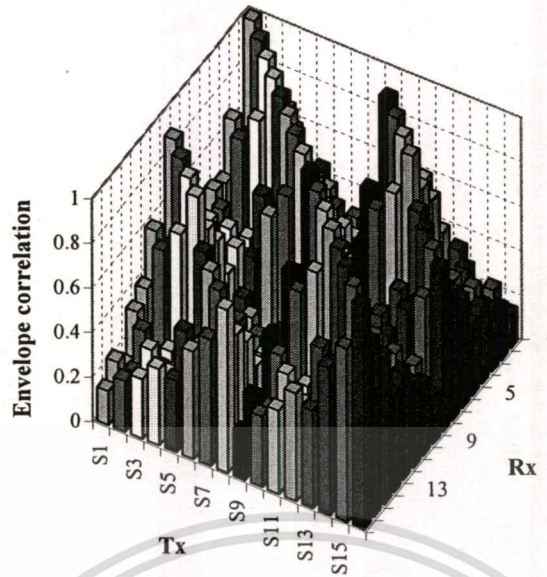


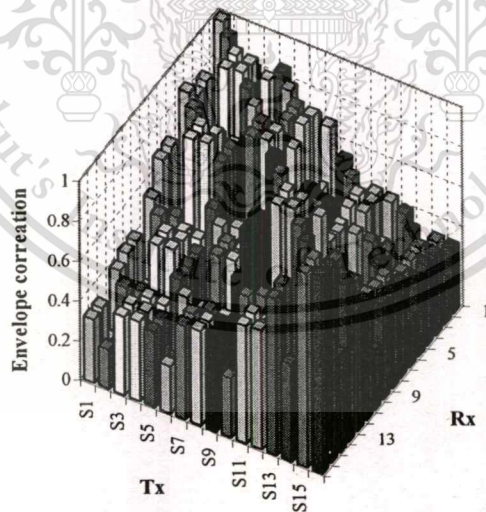
Figure 5.29 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyxx$  bias format at receiving side with an average magnitude of envelope correlation of 0.42.

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**Figure 5.30** Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyxy$  bias format at receiving side with an average magnitude of envelope correlation of 0.46.



**Figure 5.31** Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xxyy$  bias format at receiving side with an average magnitude of envelope correlation of 0.49.

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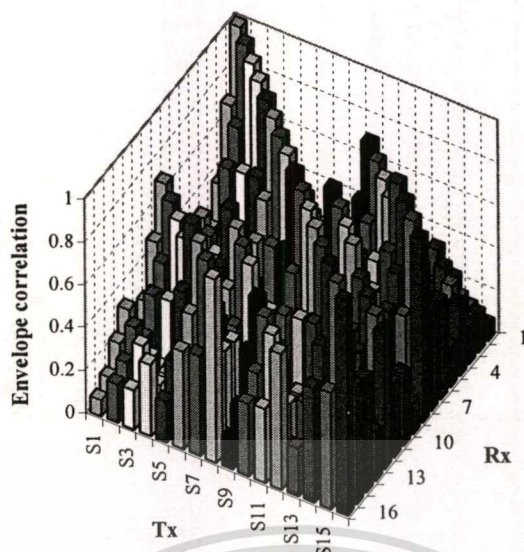


Figure 5.32 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with yyx bias format at receiving side with an average magnitude of envelope correlation of 0.44.

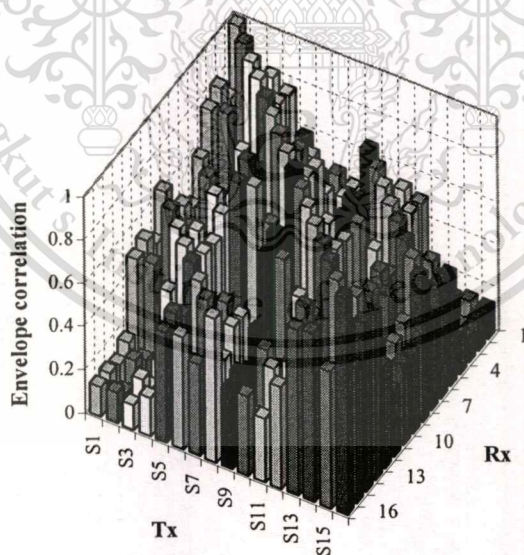


Figure 5.33 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with yxy bias format at receiving side with an average magnitude of envelope correlation of 0.45.

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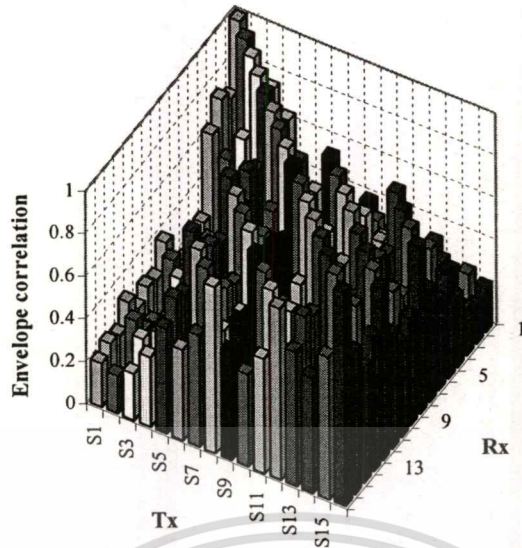


Figure 5.34 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyyy$  bias format at receiving side with an average magnitude of envelope correlation of 0.47.

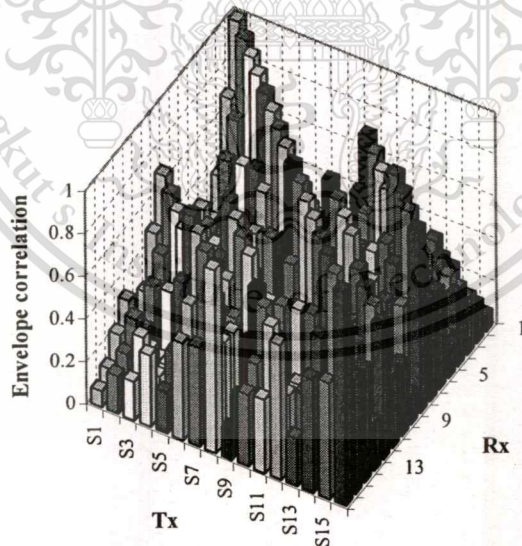
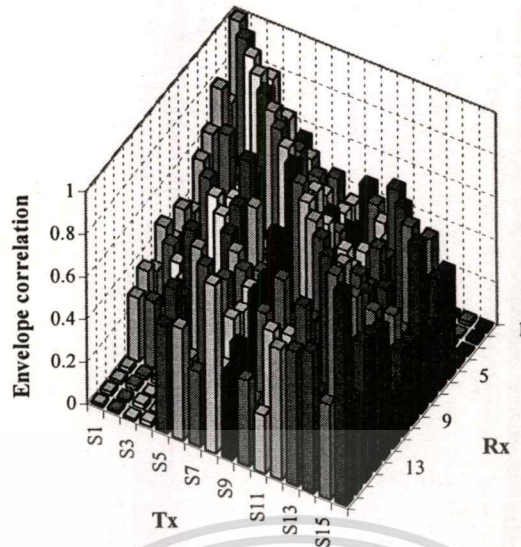


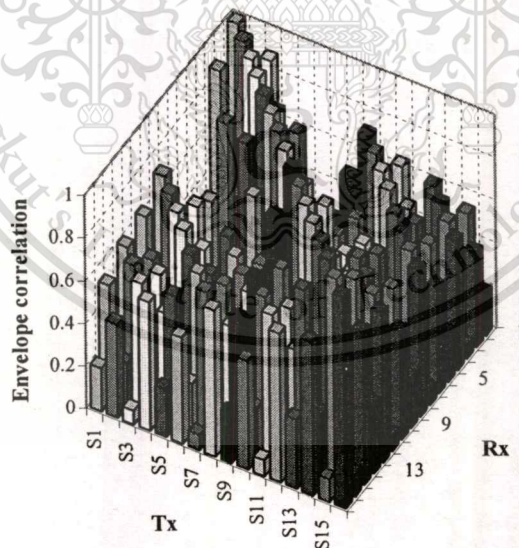
Figure 5.35 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with  $xyyy$  bias format at receiving side with an average magnitude of envelope correlation of 0.44.

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**Figure 5.36** Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements with yyyy bias format at receiving side with an average magnitude of envelope correlation of 0.44.



**Figure 5.37** Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements for main beam direction at  $45^\circ$  at the receiving side with an average magnitude of envelope correlation of 0.40.

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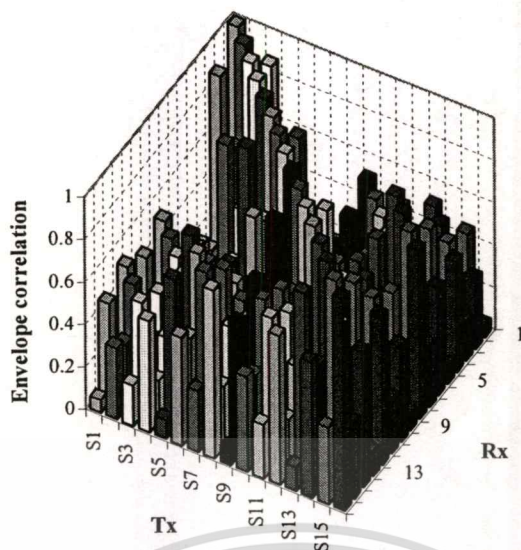


Figure 5.38 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements for main beam direction at  $135^\circ$  at the receiving side with an average magnitude of envelope correlation of 0.40.

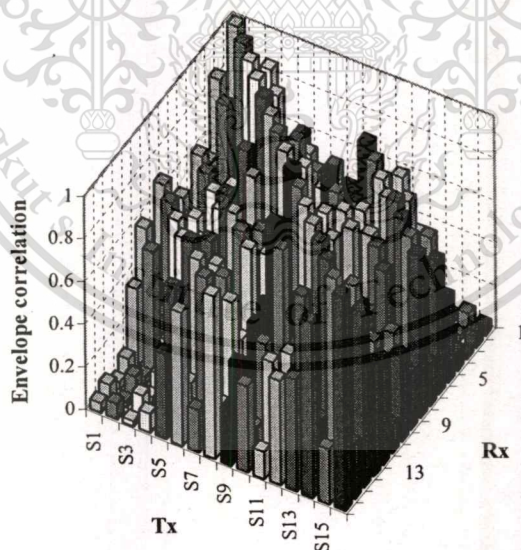
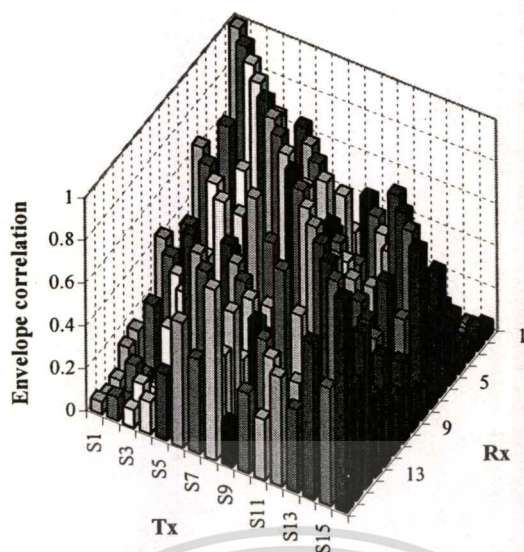


Figure 5.39 Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements for main beam direction at  $225^\circ$  at the receiving side with an average magnitude of envelope correlation of 0.43.

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**Figure 5.40** Magnitude of the envelope correlation matrix for a measured  $4 \times 4$  MIMO system using uniform linear array monopole antennas at transmitting side and a phased array antenna of switched-beam elements for main beam direction at  $315^\circ$  at the receiving side with an average magnitude of envelope correlation of 0.36.

#### 5.4 Summary

The performance of a MIMO system using switched-beam antennas have been measured and analyzed in terms of capacity, CCDF and spatial correlation. It was found that a switched-beam single patch antenna offered lower capacity than the flat four-beam phased array antenna and phased array antenna of switched-beam elements. The phased array antenna of switched-beam elements offered capacity closely to the capacities offered by the ULA and UCA of monopole antennas, in realistic correlated environment. The flat four-beam phased array antenna offered capacity higher than other switched-beam antennas. The magnitude of envelope correlation of switched-beam antennas are lower than 0.7.

Since the switched-beam antenna requires only one receiver, it could be an attractive for cost-effective indoor wireless applications. Switched-beam antennas can be implemented as a mobile antenna on the notebook computers or PDA (Personal Digital Assistance) devices for the future time.

## CHAPTER 6

# CONCLUSIONS

In this thesis, the performance of MIMO wireless communication using switched-beam antennas is studied in an indoor environment. Switched-beam antenna systems have been proposed as a solution to the increasing of user demand for high data rate and cost-effective wireless applications.

### 6.1 Discussion for simulation and experimental results

The simulation results and the experimental results are different between the flat four-beam antenna and the phased array antenna of switched-beam elements. In chapter 4 the channel capacity of a phased array antenna of switched-beam elements higher than a flat four-beam phased array antenna, but in chapter 5 the channel capacity of a flat four-beam phased array antenna higher than a phased array antenna of switched-beam elements. We tried to adjust the ring of scatterers in the two-ring model by decreasing and increasing the ring radius to 3.5 meters and 4.5 meters. The CCDF results are plotted in Figure 6.1 and Figure 6.2. The simulation results are not different with the simulation results in chapter 4 due to the parameters in the model may not be appropriated. Some parameters such as polarization of wave should be considered in the future research. Another model such as ray-tracing model may be more appropriated for simulation.

### 6.2 Summary

The literature reviews on wireless communication are given in chapter 1. The principles of MIMO wireless communications system is introduced in chapter 2. They can potentially achieve very high spectral efficiencies, because they decompose the channel to several parallel subchannels. Their efficiency depends on the propagation environment between the transmitter and the receiver array. In chapter 3, the switched-beam antennas configurations are presented and the performance improvement by using switched-beam antennas is introduced. In chapter 4, the physical channel models

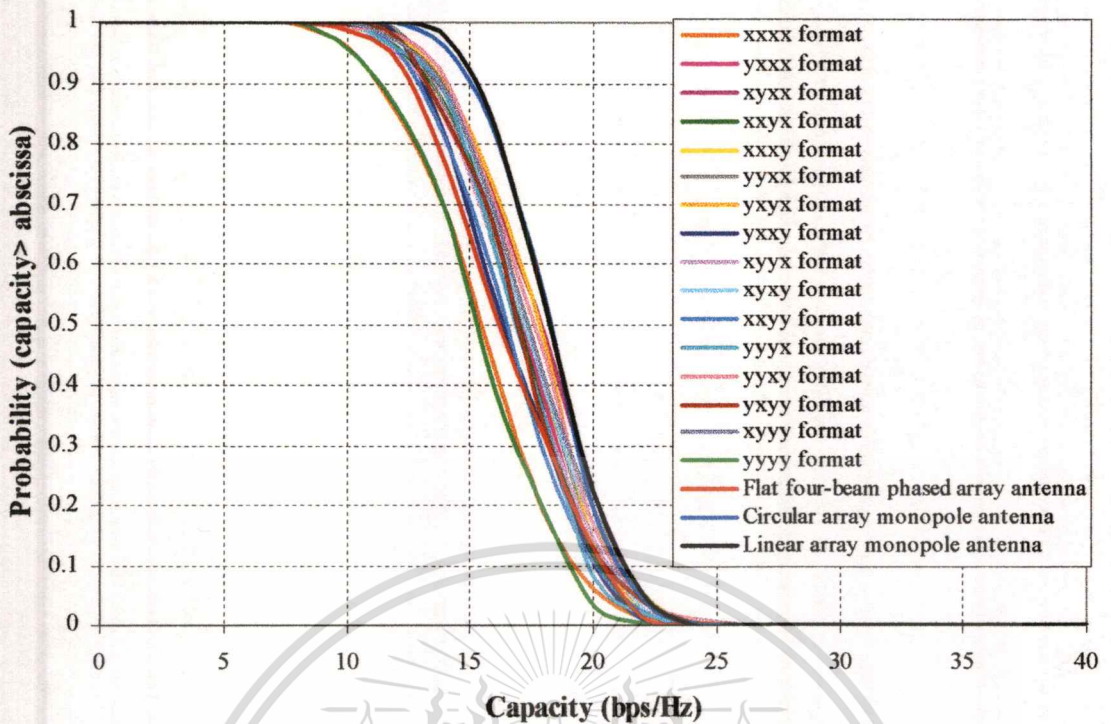


Figure 6.1 CCDF of MIMO system using switched-beam antenna with four-element transmitting antenna based on the simulation results with the ring radius of 3.5 meters.

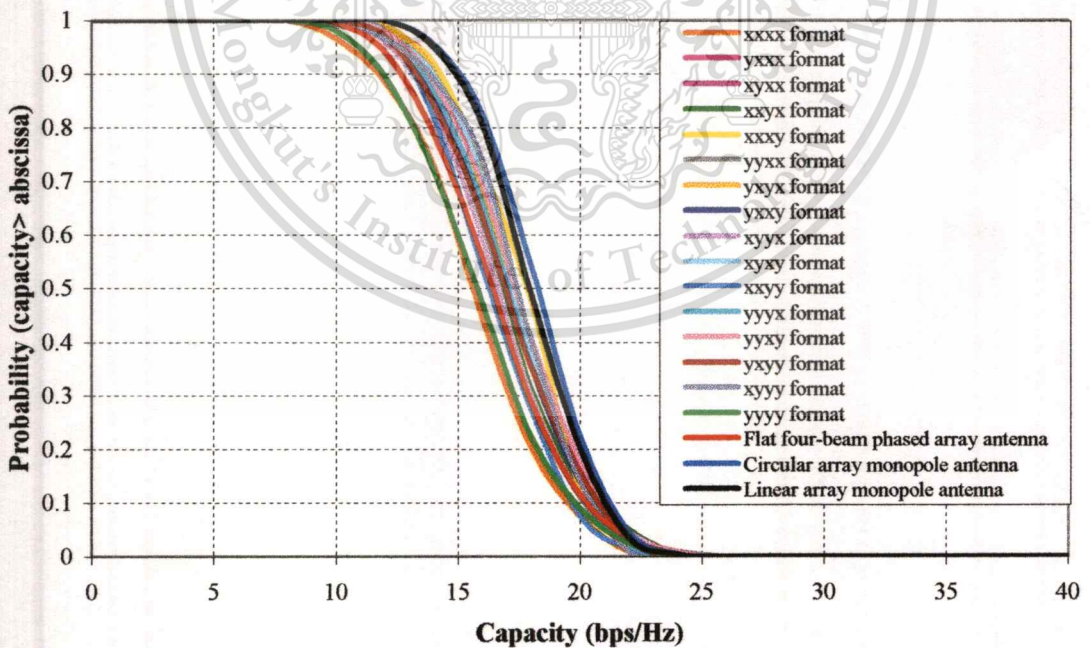


Figure 6.2 CCDF of MIMO system using switched-beam antenna with four-element transmitting antenna based on the simulation results with the ring radius of 4.5 meters.

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based on one-ring model and two-ring model are used to simulate the performance of switched-beam antennas in MIMO indoor wireless channels. At an SNR of 20 dB with 90% probability, the CCDF results show that the channel capacity of switched-beam single patch antenna for a  $2 \times 2$  MIMO wireless channel exceeds 6.5 bps/Hz. It is lower than two monopole antennas by 0.5 bps/Hz. For a  $4 \times 4$  MIMO wireless channel, a flat four-beam phased array antenna and a phased array antenna of switched beam elements, the channel capacities exceed 12.6 bps/Hz and 11 bps/Hz, respectively. Chapter 5 presents the measurement results of switched-beam antennas. The CCDF of measured capacity shows that the channel capacity of a switched-beam single patch for a  $2 \times 2$  MIMO wireless channel exceeds 7.20 bps/Hz, at 90 % probability and an SNR of 20 dB. For a  $4 \times 4$  MIMO wireless channel, a flat four-beam phased array antenna and a phased array antenna of switched beam elements, the channel capacities exceed 19.80 bps/Hz and 12.80 bps/Hz, respectively. For four-element ULA and UCA of monopole antenna, the channel capacities are more than 20.80 bps/Hz and 18.20 bps/Hz. The channel characteristic when using switched-beam antennas are presented as the correlated channel.

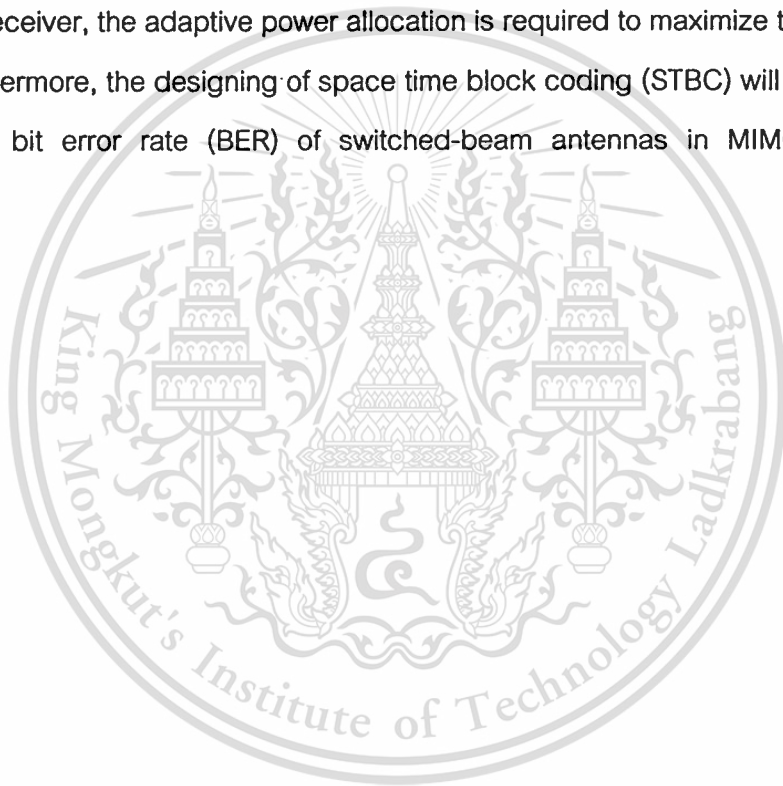
In this thesis we used the array of monopole antenna as a reference antenna, because it is easy to implement and there is low cost structure. The dimension of the antenna array is narrow than the switched-beam antennas, but longer and higher than the switched-beam antennas. The switched-beam antennas are low profile and is easier to mounted on mobile devices, but the implementation of switched-beam antennas are complicated than the monopole antenna. The performance of the antenna array (monopole) is higher than the switched-beam antenna, but the antenna array requires high cost of multiple radio transceivers. When compared with the switched-parasitic antenna [26] the switched-beam antennas in this thesis are more compacted in size than the switched parasitic antenna. Because the switched-parasitic antenna is used the monopole antenna as array elements.

From the studies, we found that the performance of a flat four-beam phased array antenna and a phased array antenna of switched-beam elements have the channel capacity close to the capacity given by the antenna array. A flat four-beam phased array antenna is very interesting, because it provides the highest channel

capacity in realistic indoor environment and is easier to implement than a phased array antenna of switched-beam elements. Furthermore, the switched-beam antenna requires only one receiver, it could be an attractive low cost solution for future user terminals.

### 6.3 Future Study

For further research, the development of accuracy channel modeling is required. Algorithms for controlling the switched-beam antennas are required to study. Direction of arrival (DOA) estimation has to be studied in the switched-beam process, to find the incoming signals and switch the main beam to the mobile terminal. When the channel is known at the receiver, the adaptive power allocation is required to maximize the channel capacity. Furthermore, the designing of space time block coding (STBC) will be studied for evaluating bit error rate (BER) of switched-beam antennas in MIMO wireless channels.



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## AUTHOR BIOGRAPHY

**Author:** Mr.Prasit Inthong

**Date of Birth:** November 7, 1977

**Place of Birth:** Chumphon Province, Thailand

**Bachelor Degree:** B.Eng. in Electronic and Telecommunication Engineering Institute:  
Department of Electronic and Telecommunication Engineering,  
Faculty of Engineering, King Mongkut's University of Technology  
Thonburi

**Year of Graduation:** 2001

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