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ภาคผนวก

ภาคผนวก ก

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บทความวิจัยที่ได้รับการตีพิมพ์เผยแพร่ในวารสารวิชาการระดับชาติ

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ภาคผนวก ข

บทความวิจัยที่ได้รับการตีพิมพ์

THE IMPROVEMENT OF MIMO CAPACITY USING SIMPLE TECHNIQUE REALIZED BY BUTLER MATRIX

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Abstract

In the literature, among many techniques improving MIMO capacity (Foschini, 1996; Foschini *et al.*, 1998; Kermoal *et al.*, 2000; Molsch *et al.*, 2002; Stridh *et al.*, 2000; Telatar, 1995; Tsoulos, 2006; Vieira *et al.*, 2006), the concept of eigen-beamforming has been recognized as the best technique to provide an enhanced capacity. However, the expense of this technique is the cost of feedback channel and complexity processing. Therefore, this article aims to present a simple technique based on angle domain processing which does not require a feedback channel and has low complexity. A Butler matrix is chosen for 4 × 4 MIMO systems in order to prove the concept of the proposed system in practice. The simulation and measurement results indicate the enhancement of MIMO capacity when using Butler matrix.

Keywords: MIMO Channel Capacity, Array domain processing, Angle domain processing, Eigen-beamforming, Butler matrix

Introduction

So far in the literature, the MIMO (Multiple Input Multiple Output) systems provide a promising quality of service including a great channel capacity. Many works have proposed the method of eigen beamforming technique (Bishwarup *et al.*, 2006; Liang Sun *et al.*, 2009; Sirikiat *et al.*, 2006; Xiayu Zheng *et al.*, 2007;) to improve the capacity. This technique utilizes the properties of estimated channels by performing singular value decomposition on channel matrix. Then, eigen-vectors compositing of channel matrix are considered as pre and post coding schemes for MIMO systems. From analysis, the eigen

beamforming offers the optimal performance in comparing with other techniques. However, the drawback of this technique is the requirement of feedback channel information which increases the overhead of data transmission and the expense of data processing. In addition, the complexity of pre and post coding is so difficult that it is unattractive to be implemented for real application. Therefore, the search of new technique to replace eigen-beamforming technique is still in focus.

In this article, the simple technique based on the concept of angle domain processing is introduced. This is because angle domain

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processing does not require any additional complexity like feedback channel for pre and post coding schemes. Instead, their schemes are designed by fixed angles of arrival and departure which operate as blind switched beamforming. Although the performance of angle domain processing can be predicted to be lower than eigen-beamforming but the ease of implementation might be a good tradeoff to attract MIMO designers. Also in this article, the practical realization of the proposed system has been demonstrated by using Butler matrix. A low profile manufacturing is constructed and also tested under real environments. By only inserting Butler matrix next to antenna arrays at both transmitter and receiver, the improvement of MIMO capacity is able to be obtained as reported in simulations and measurements.

MIMO System Model

A. Array domain processing

This section details the array domain representation of MIMO systems (Tse and Viswanath, 2005). Let \mathbf{x} be a vector of the transmitted signals with N_t transmitted antennas and \mathbf{y} be a vector of the received signals with N_r received antennas. Then, the relation between transmitted and received signals is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad (1)$$

Where \mathbf{n} is an $(N_r - 1)$ noise vector and \mathbf{H} is an $(N_r \times N_t)$ channel matrix. With this notation channel output sequence can be written in matrix form as:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{N_r} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_t} \\ h_{21} & h_{22} & \dots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r 1} & h_{N_r 2} & \dots & h_{N_r N_t} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{N_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{N_r} \end{bmatrix} \quad (2)$$

Figure 1 shows the angle domain representation of MIMO systems. There is an

arbitrary number of physical paths between the transmitter and receiver; the i th path having attenuation of α_i , makes an angle of φ_t ($\square_t := \cos\varphi_t$) with the transmit antenna array and angle of φ_r ($\square_r := \cos\varphi_r$) with the receive antenna array. The channel matrix \mathbf{H} can be written as:

$$\mathbf{H} = \sum_i \alpha_i \mathbf{e}_r(\Omega_i) \mathbf{e}_t(\Omega_i)^H \quad (3)$$

Where

$$\alpha_i = \alpha \sqrt{N_t N_r} \exp\left(\frac{j2\pi d_i}{\lambda}\right) \quad (4)$$

$$\mathbf{e}_t(\Omega) = \frac{1}{\sqrt{N_t}} \begin{bmatrix} 1 \\ \exp[-j(2\pi \Delta_t \square_t)] \\ \vdots \\ \exp[-j(N_t - 1)(2\pi \Delta_t \square_t)] \end{bmatrix} \quad (5)$$

And

$$\mathbf{e}_r(\Omega) = \frac{1}{\sqrt{N_r}} \begin{bmatrix} 1 \\ \exp[-j(2\pi \Delta_r \square_r)] \\ \vdots \\ \exp[-j(N_r - 1)(2\pi \Delta_r \square_r)] \end{bmatrix} \quad (6)$$

Also, α is the distance between transmit and receive antennas along path i th. The vector $\mathbf{e}_t(\square)$ and the vector $\mathbf{e}_r(\square)$ are, respectively transmitted and received unit spatial signatures along the direction \square . λ is the wavelength of the center frequency in the whole signal bandwidth. Δ_t is the normalized transmit antenna separation and Δ_r is the normalized receive antenna separation. When Channel State Information (CSI) is not available at the transmitter, the capacity of MIMO systems expressed in bits per second per hertz (bps/Hz) can be written as

$$C = \log_2 \det \left(\mathbf{I}_{N_r} + \frac{P}{P_t N_t} \mathbf{H} \mathbf{H}^H \right) \quad (7)$$

where \mathbf{I}_{N_r} is the identity matrix of size $N_r \times N_r$, \mathbf{H} is the channel matrix of size $N_r \times N_t$ with \mathbf{H}^H being its transpose conjugate, and P , gives

the average Signal-to-Noise Ratio (SNR) per receiver branch independent of the number of transmitting antennas N_t .

B. Angle domain processing

The concept of angle domain (Li *et al.*, 2007-2008) can be represented by the transmitted and received signals. The signal arriving at a directional \square onto the receive antenna array is along the unit spatial signature $\mathbf{e}_r(\square)$ given by (6). Hence, the N_r fixed vector is given by

$$\xi_r = \left\{ e_r(0), e_r\left(\frac{1}{L_r}\right), \dots, e_r\left(\frac{N_r-1}{L_r}\right) \right\} \quad (8)$$

In (8), it can be noticed that there is a set of orthogonal basis for the received signal space. This basis provides the representation of received signals in the angle domain.

It is similarly defined for the angle domain representation of the transmitted signal. The signal transmitted at direction \square is along the unit vector $\mathbf{e}_t(\square)$, defined in (5). The N_t fixed vector is given by

$$\xi_t = \left\{ e_t(0), e_t\left(\frac{1}{L_t}\right), \dots, e_t\left(\frac{N_t-1}{L_t}\right) \right\} \quad (9)$$

Where $L_t = N_t \Delta_t$ and $L_r = N_r \Delta_r$ are the normalized antenna array lengths of the

transmitter and receiver, respectively. Let \mathbf{U}_t and \mathbf{U}_r be the unitary matrices whose columns are the basis vector in (8) and (9), respectively, can be written as:

$$\mathbf{U}_t = \frac{1}{\sqrt{N_t}} \exp\left(\frac{-j2\pi k l}{N_t}\right) \quad k, l = 0, 1, \dots, N_t - 1 \quad (10)$$

And

$$\mathbf{U}_r = \frac{1}{\sqrt{N_r}} \exp\left(\frac{-j2\pi k l}{N_r}\right) \quad k, l = 0, 1, \dots, N_r - 1 \quad (11)$$

We can transform the array domain into the angle domain by

$$\mathbf{H}^a = \mathbf{U}_r^H \mathbf{H} \mathbf{U}_t \quad (12)$$

Thus, the capacity of MIMO systems is given by

$$C = \log_2 \det \left(\mathbf{I}_{N_r} + \frac{\rho}{N_r N_t} \mathbf{H}^a \mathbf{H}^{aH} \right) \quad (13)$$

Where \mathbf{I}_{N_r} is the identity matrix of size $N_r \times N_r$, \mathbf{H}^a is the channel matrix of size $N_r \times N_t$.

Figure 2 shows the simulated channel matrices from statistical modeling adopted by Fundamentals of Wireless Communication book. The basis for the statistical modeling of MIMO fading channels is approximated by

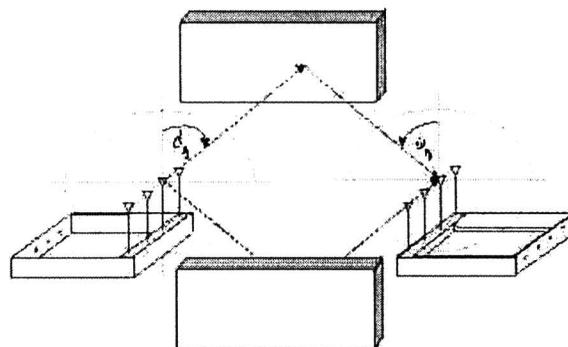


Figure 1. Angle domain representations of 4 x 4 MIMO channel with four transmit and receive antennas

the physical paths partitioning into angularly resolvable bins and aggregated to form resolvable paths whose channel gains are H_k . Assuming that all of the physical paths is independent. Then, we used equations (3)-(6) to find channel matrix for array domain and (10)-(12) to find channel matrix for angle domain.

C. Eigen beamforming technique

We used the channel matrix H from array domain processing. Consider a MIMO channel with $N_t \times N_r$ channel matrix H that is known to both the transmitter and the receiver, the singular value can be found by using SVD technique in MATLAB programming. We can obtain its singular value decomposition (SVD) as

$$H = U \Sigma V^H \quad (14)$$

Where $N_t \times N_t$ matrix U and the $N_r \times N_r$ matrix V are unitary matrices, Σ is an $N_t \times N_r$ diagonal matrix. So, the capacity of MIMO system is given by

$$C = \log_2 \det \left(I_{N_r} + \frac{P_t}{P_r N_r} \Sigma \Sigma^H \right) \quad (15)$$

Practical realization using Butler Matrix

Figure 3 shows a block diagram of Butler matrix (Liberti and Rappaport, 1999) which is applied for the concept of angle domain processing for 4 x 4 MIMO systems. The fixed beamforming matrix is bi-direction, which means that each port corresponds to particular received as well as transmitted signals from the same radiation pattern.

It is clearly shown that the weight vectors corresponding to each port in Table 1 are mutually orthogonal. Therefore, instead of using (10) and (11), the basis vector of applying Butler matrix can be written by the following:

$$B_p = e^{-j2\pi p k} \quad k, l = 0, 1, \dots, N_p - 1 \quad (16)$$

And

$$R_p = e^{-j2\pi p k} \quad k, l = 0, 1, \dots, N_p - 1 \quad (17)$$

Figure 4 shows a configuration of manufactured Butler matrix. The dimensions in Butler matrix can be calculated from transmission line theory. The manufactured

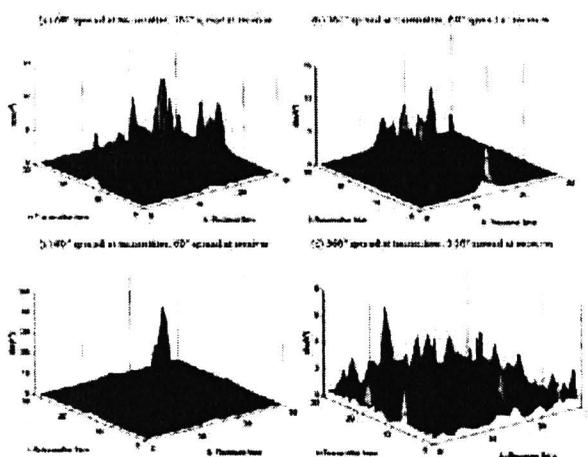


Figure 2. An example of with different angle spreads at the transmitter and receiver

product is also confirmed by measuring inter-element phasing and beam direction which are shown in Table 2. In Table 2, the distributions of all inter-element phasing are similar to conceptual Butler matrix but they are slightly deviated by ± 10 degree. However, the beam direction is deviated by just only 0.6 degree.

Figure 5. illustrates the beam direction of applying Butler matrix to both transmitter and receiver. It is interesting to see that the concept of angle domain processing is successfully achieved by simply adding Butler matrices next to antenna elements. Then, the channel matrix realized by Butler matrix can be written as:

$$H' := B_r H B_t \tag{18}$$

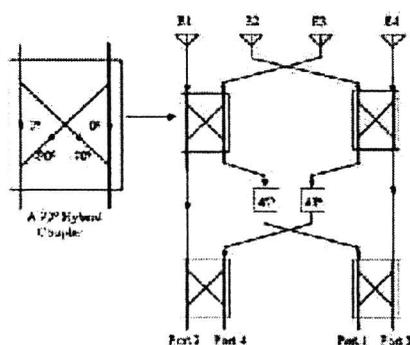


Figure 3. A Block diagram of Butler matrix

Where B_t and B_r are the unitary matrices whose columns are the basis vector in four direction for transmitter and receiver and H is channel matrix of size $N_r \times N_t$ to get array domain. Thus, the capacity of MIMO systems when applying Butler matrix is given by

$$C = \log_2 \det \left(\mathbf{I}_{N_r} + \frac{P_t}{P_r N_t} \mathbf{H}^H \mathbf{H} \right) \tag{19}$$

Measurement

Figure 6 shows a block diagram of measurement set up for 4 × 4 MIMO system. The network analyzer is used for measurement channel coefficients in magnitude and phase. The power amplifier (PA) is used at transmitter to provide more transmitted power. Low noise



Figure 4. Configuration of manufactured Butler matrix

Table 1. Element phasing, beam direction and inter-element phasing for the Butler matrix shown in Figure 3 (Conceptual)

θ	E1 ($k=1$)	E2 ($k=2$)	E3 ($k=3$)	E4 ($k=4$)	Beam Direction	Inter-Element Phasing
Port 1 ($k=1$)	-45°	-180°	45°	-90°	138.6°	-135°
Port 2 ($k=2$)	0°	-45°	90°	135°	104.5°	-45°
Port 3 ($k=3$)	-135°	90°	-45°	0°	75.5°	45°
Port 4 ($k=4$)	-90°	-45°	-180°	-45°	41.4°	135°

considered as (i) 60° spread at transmitter and 360° spread at receiver, denoted as 60-360 (ii) 360° spread at transmitter and 60° spread at receiver, denoted as 360-60 (iii) 60° spread at transmitter and 60° spread at receiver, denoted as 60-60 (iv) 360° spread at transmitter and 360° spread at receiver, denoted as 360-360. Note that case (iii) is equivalent to line of sight scenario while case (iv) is equivalent to Rayleigh fading channel.

In Figure 8, the capacity comparison between 4 × 4 MIMO systems with array domain processing, angle domain processing and eigen-beamforming technique is presented.

The results indicate that to use angle domain processing realized by Butler matrix can improve the channel capacity for any fading conditions. The range of capacity enhancement is from 5 to 10 dB depending on characteristic of fading. However, the optimum eigen-beamforming technique offers a better performance than angle domain processing.

B. Measurement results

The channel matrix H and H^H is found by measured data from network analyzer. The channel fading environments are measured by changing the locations of receiver. Five locations

Table 2. Element phasing, beam direction and inter-element phasing for the Butler matrix shown in Figure 4 (Manufactured)

θ	E1 ($k=1$)	E2 ($k=2$)	E3 ($k=3$)	E4 ($k=4$)	Beam Direction	Inter-Element Phasing
Port 1 ($k=1$)	158°	25°	-112°	118°	138°	-130°
Port 2 ($k=2$)	-87°	-137°	176°	137°	105°	132°
Port 3 ($k=3$)	176°	-130°	-98°	76°	-42°	50°
Port 4 ($k=4$)	136°	-90°	40°	176°	42°	138°

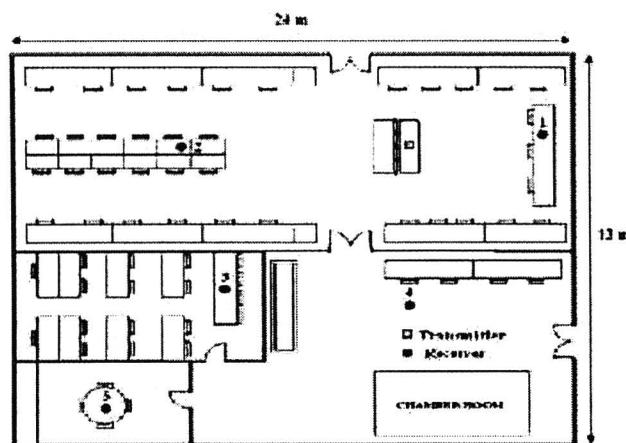


Figure 7. Measurement scenarios

are considered in Figure 7. We also believe that the mismatches among RF circuits in transmit/receive components and mutual coupling effects are included in the measured channel. The simulations are undertaken by utilizing measured data into MATLAB programming and the capacity results are evaluated by using (7), (15) and (19).

Figure 9 shows comparison between array and angle domain channels of 4 x 4 MIMO systems at location 5, where H_{ij} is referred to the channel coefficient at i th receive antenna and j th transmit antenna. It can be

observed that channels of array domain processing and angle domain processing are quite different. The amplitude deviation is about ± 5 dB and the phase deviation is about $\pm 100^\circ$. These deviations are dominant to the capacity performance of MIMO system. For other locations, the deviations of amplitude and phase are similar to location 5.

In Figure 10, the average capacity by averaging overall locations versus signal to noise ratio (SNR) is presented. The results indicate that to use the angle domain processing realized by Butler matrix offers better performance than array domain processing. However, the best performance is achieved by the optimum eigen-beamforming technique. In order to justify the results, the numeric values of average capacity at SNR = 10 dB are given in Table 3. It is noticed that the benefit of angle domain processing is more pronounced at location 1 and 5. The reason is that these locations are close to wall and there are many surrounding furniture providing more multipath. However, the improvement of MIMO capacity can be observed from all locations with a little expense of inserting Butler matrices at both transmitter and receiver.

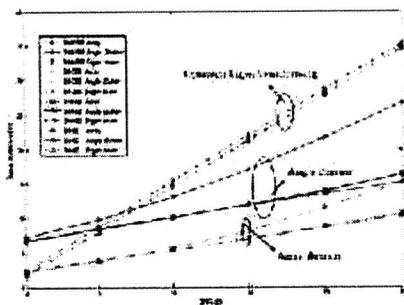


Figure 8. Average capacity (bits/s/Hz) vs. SNR (dB) for 4 conditions of angle spread, $\Delta\alpha = \Delta\theta = 0.5$

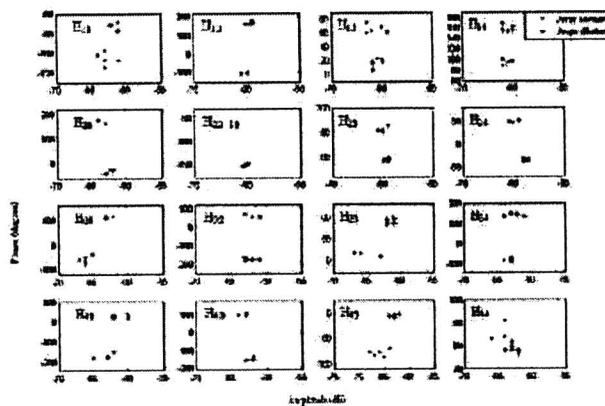


Figure 9. Measured 4 x 4 MIMO channels of array domain processing and angle domain processing (Butler matrix), at location 5

In Table 4, result comparisons between array domain processing, angle domain processing and eigen-beamforming technique. The complexity of eigen-beamforming can be reduced by using the propose system. However,

the capacity of propose system is 8.74 bits/s/Hz lower than the eigen-beamforming technique. This is the tradeoff between using both techniques in which the MIMO designers have to realize.

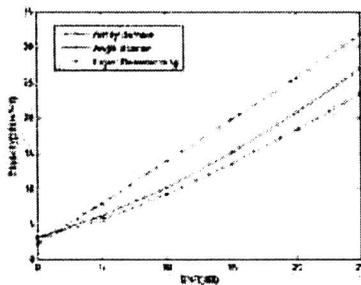


Figure 10. Average capacity (bits/s/Hz) vs. SNR (dB) at each location

Conclusions

This article presents the performance of MIMO systems using angle domain processing realized by Butler matrix. The simulation result reveals that the proposed system outperforms the conventional array domain processing for every fading case. And then, this paper verifies the benefit of using angle domain processing for 4 × 4 MIMO systems by measured results. The angle domain processing realized by Butler matrix is implemented and compared with array domain processing. The results reveal that the angle domain processing

Table 3. Average capacity at over all locations for SNR=10 dB

Location	Average capacity (bits/s/Hz)		
	Array domain	Angle domain (Butler matrix)	Eigen beamforming
1	8.72	10.12	13.93
2	8.43	8.52	14.72
3	6.46	6.65	15.12
4	6.88	7.37	15.75
5	10.57	11.03	10.62

Table 4. Result comparisons between array domain processing, angle domain processing (Butler matrix) and eigen-beamforming technique

Processing	Array domain	Angle domain (Butler matrix)	Eigen beamforming
Complexity in processing	None	None	Additional SVD technique
Complexity in feedback	None	None	Additional algorithms for feedback channel
Complexity in hardware	None	Additional butler matrix	None
Average capacity (bits/s/Hz) at SNR=10 dB	8.21	8.74	14.03

outperforms the conventional array domain processing for all fading locations. Hence, the proposed system is attractive to be practically implemented on MIMO systems due to its ease and low complexity.

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Performance of MIMO Capacity using Angle Domain Processing Realized by Butler Matrix

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Abstract—This paper aims to present the benefit of using a Butler matrix for MIMO systems employing angle domain processing instead of array domain processing. By applying Butler matrix, the concept of angle domain processing can be realized in practice and it still takes a full advantage of multiple antennas. The different scenarios of a fading MIMO environments are examined. The simulation results on channel capacity indicate that the angle domain processing with Butler matrix outperforms the conventional array domain processing. Also the proposed system is attractive to MIMO implementation due to its low cost and complexity.

Index terms—MIMO capacity, Angular spread, Butler matrix, Angle domain processing, Array domain processing.

I. INTRODUCTION

In the research area of MIMO systems, many works have been proposed to enhance the channel capacity in order to satisfy the user demand for high data rate applications [1]-[4]. Some studies have been focused on theoretical works and some are performed by measurements. Nevertheless, most of them develop the technique enhancing channel capacity through channel behavior [5]-[7]. It can be noticed that the general consideration of channel capacity is based on the array antennas at both transmitter and receiver but the channel behavior is considered by many angle parameters such as angle of arrival, angle of departure and angle spread. Therefore, it is interesting to investigate the performance of MIMO systems using angle domain processing instead of conventional array domain. Recently, the authors in [9] develop the channel estimation of MIMO-OFDM system based on angle domain consideration. The applicability of angle domain technique is dependent on the channel stochastic information available to the receiver. The design of suitable pilots is proposed by facilitating the direct implementation of angle domain and analyzing the performances of different channel estimation techniques. Although the significant improvement on MIMO capacity can be expected by using angle domain processing but, so far in literature, there is no work to illustrate the capacity benefit of using angle domain processing. The reason is that the pre and post coding schemes of angle domain transformations increase the complexity on both transmitter and receiver. Hence, it challenges to find the technique with low cost and complexity matching with the concept of angle domain processing.

In this paper, the advantage of using angle domain instead of array domain processing is presented. Also the low profile concept of angle domain processing which is convenient for implementation is proposed by using Butler matrix. This

matrix simultaneously forms multiple beams into four directions. By only inserting Butler matrix before antenna array, the conventional MIMO systems can be transformed into the MIMO systems with angle domain processing without the need of additional burden on processing units at both transmitter and receiver. Also it is low cost, uncomplicated and easy to implement so the proposed system is attractive to be used in practice.

The paper is organized as follows. In section II, the details of both array domain and angle domain are described. Then, the feature of Butler matrix to apply for angle domain processing is given in section III. Section IV provides the simulation results of angle domain realized by Butler matrix in comparing with conventional array domain. Finally in section V, the conclusion of this paper is given.

II. MIMO SYSTEMS MODEL

A. Array domain

This section details the array domain representation of MIMO systems. Let \mathbf{x} be a vector of the transmitted signals with N_t transmitted antennas and \mathbf{y} be a vector of the received signals with N_r received antennas. Then the relation between transmitted and received signals is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad (1)$$

where \mathbf{n} is an $(N_r \times 1)$ noise vector and \mathbf{H} is an $(N_r \times N_t)$ channel matrix. With this notation channel output sequence can be written in matrix form as:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{N_r} \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,N_t} \\ h_{2,1} & h_{2,2} & \dots & h_{2,N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \dots & h_{N_r,N_t} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{N_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{N_r} \end{bmatrix} \quad (2)$$

Fig.1 shows the angle domain representation of MIMO systems. There is an arbitrary number of physical paths between the transmitter and receiver [8]; the i th path having attenuation of a_i , makes an angle of ϕ_{t_i} ($\Omega_{t_i} = \cos \phi_{t_i}$) with the transmit antenna array and an angle of ϕ_{r_i} ($\Omega_{r_i} = \cos \phi_{r_i}$) with the receive antenna array. The channel matrix \mathbf{H} can be written as:

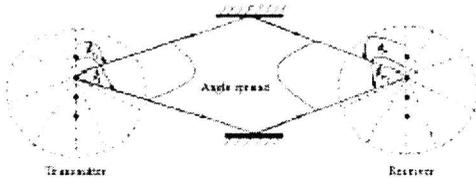


Fig.1 Angle-domain representation of MIMO channel with four transmit and receive antennas.

$$\mathbf{H} = \sum_i d_i^* \mathbf{e}_t(\Omega_i) \mathbf{e}_r(\Omega_i)^* \quad (3)$$

where

$$d_i^* = \alpha \sqrt{N_t N_r} \exp\left(\frac{j2\pi d_i}{\lambda_c}\right) \quad (4)$$

$$\mathbf{e}_t(\Omega) = \frac{1}{\sqrt{N_t}} \begin{bmatrix} 1 \\ \exp[-j(2\pi\Delta)\Omega] \\ \vdots \\ \exp[-j(N_t-1)(2\pi\Delta)\Omega] \end{bmatrix} \quad (5)$$

And

$$\mathbf{e}_r(\Omega) = \frac{1}{\sqrt{N_r}} \begin{bmatrix} 1 \\ \exp[-j(2\pi\Delta_r)\Omega] \\ \vdots \\ \exp[-j(N_r-1)(2\pi\Delta_r)\Omega] \end{bmatrix} \quad (6)$$

Also, d_i is the distance between transmit and receive antennas along path i th. The vector $\mathbf{e}_t(\Omega)$ and $\mathbf{e}_r(\Omega)$ are, respectively, the transmitted and received unit spatial signatures along the direction Ω , λ_c is the wavelength of the center frequency in the whole signal bandwidth. Δ is the normalized transmit antenna separation and Δ_r is the normalized receive antenna separation. When Channel State Information (CSI) is not available at the transmitter, the capacity of MIMO systems [11] expressed in bits per second per hertz (bps/Hz) can be written as

$$C = \log_2 \det \left(\mathbf{I}_{N_r} + \frac{P_t}{P_n N_r} \mathbf{H} \mathbf{H}^* \right) \quad (7)$$

where \mathbf{I}_{N_r} is the identity matrix of size $N_r \times N_r$, \mathbf{H} is the channel matrix of size $N_r \times N_t$, with \mathbf{H}^* being its transpose conjugate, and P_t gives the average Signal-to-Noise Ratio (SNR) per receiver branch independent of the number of transmitting antennas N_t .

B. Angle domain

The concept of angle domain can be represented by the transmitted and received signals. The signal arriving at a directional cosine Ω onto the receive antenna array is along the unit spatial signature $\mathbf{e}_r(\Omega)$ given by (5). Hence, the N_r fixed vector is given by

$$\xi_r = \left\{ \mathbf{e}_r(0), \mathbf{e}_r\left(\frac{1}{L_r}\right), \dots, \mathbf{e}_r\left(\frac{N_r-1}{L_r}\right) \right\} \quad (8)$$

In (8), it can be noticed that there is a set of orthonormal basis for the received signal space. This basis provides the representation of received signals in the angular domain.

It is similarly defined for the angular domain representation of the transmitted signal. The signal transmitted at direction Ω is along the unit vector $\mathbf{e}_t(\Omega)$, defined in (5). The N_t fixed vector is given by

$$\xi_t = \left\{ \mathbf{e}_t(0), \mathbf{e}_t\left(\frac{1}{L_t}\right), \dots, \mathbf{e}_t\left(\frac{N_t-1}{L_t}\right) \right\} \quad (9)$$

where $L_t = N_t \Delta_t$ and $L_r = N_r \Delta_r$ are the normalized antenna array lengths of the transmitter and receiver [9], respectively. Let \mathbf{U}_t and \mathbf{U}_r be the unitary matrices whose columns are the basis vector in (8) and (9), respectively, can be written as:

$$\mathbf{U}_t = \frac{1}{\sqrt{N_t}} \exp\left(\frac{-j2\pi k l}{N_t}\right) \quad k, l = 0, 1, \dots, N_t - 1 \quad (10)$$

And

$$\mathbf{U}_r = \frac{1}{\sqrt{N_r}} \exp\left(\frac{-j2\pi k l}{N_r}\right) \quad k, l = 0, 1, \dots, N_r - 1 \quad (11)$$

We can transform the array domain into the angle domain by

$$\mathbf{H}^* = \mathbf{U}_r^* \mathbf{H} \mathbf{U}_t \quad (12)$$

Thus, the capacity of MIMO systems given by

$$C = \log_2 \det \left(\mathbf{I}_{N_r} + \frac{P_t}{P_n N_r} \mathbf{H}^* \mathbf{H} \right) \quad (13)$$

where \mathbf{I}_{N_r} is the identity matrix of size $N_r \times N_r$, \mathbf{H}^* is the channel matrix of size $N_r \times N_t$.

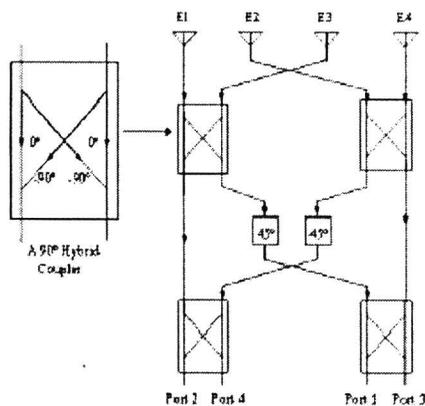


Fig. 2 A block diagram of Butler Matrix [10]

III. PRACTICAL REALIZATION USING BUTLER MATRIX

Fig. 2 shows a block diagram of Butler matrix [10] which is applied for the concept of angle domain processing for 4x4 MIMO systems. The fixed beamforming matrix is bi-direction, which means that each port corresponding to a particular received as well as transmitted signals from the same radiation pattern.

It is easily shown that the weight vectors corresponding to each port in TABLE I are mutually orthogonal. Therefore, instead of using (10) and (11), the basis vector of applying Butler matrix can be written by the following:

$$B_l = e^{-j\theta_{kl}} \quad k, l = 0, 1, \dots, N_s - 1 \quad (14)$$

And

$$B_r = e^{-j\theta_{kl}} \quad k, l = 0, 1, \dots, N_s - 1 \quad (15)$$

Fig. 3 illustrates the beam direction of applying Butler matrix to both transmitter and receiver. It is interesting to see that the concept of angle domain processing is successfully achieved by simply adding Butler matrix before antenna elements. Then, the channel matrix realized by Butler matrix, can be written as:

$$H^b = B_r^* H B_t \quad (16)$$

where B_t and B_r be the unitary matrices whose columns are the basis vector in four direction for transmitter and receiver and H is channel matrix of size $N_r \times N_t$, to get array domain. Thus, the capacity of MIMO systems when applying Butler matrix is given by

$$C = \log_2 \det \left(I_{N_r} + \frac{P_t}{P_r N_r} H^b H^{b*} \right) \quad (17)$$

TABLE I
Element phasing, beam direction, and inter-element phasing for the Butler matrix shown in Fig. 2.

θ_{kl}	E1 (l=1)	E2 (l=2)	E3 (l=3)	E4 (l=4)	Beam Direction	Inter-Element Phasing
Port 1 (k=1)	-45°	-180°	45°	-90°	138.6°	-135°
Port 2 (k=2)	0°	-45°	-90°	-135°	104.5°	-45°
Port 3 (k=3)	-135°	-90°	-45°	0°	75.5°	-45°
Port 4 (k=4)	-90°	-45°	-180°	-45°	41.4°	135°

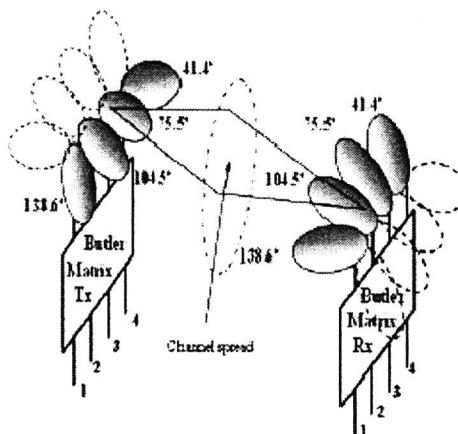


Fig. 3 An illustration of applying Butler Matrix for 4x4 MIMO systems.

IV. RESULTS AND DISCUSSIONS

The simulations are undertaken by MATLAB programming and the capacity results are evaluated by using (7) and (17). For array domain approach, the channel matrix (H) is found by assumptions in (4), (5) and (6). For angle domain approach realized by Butler matrix, it can find channel matrix (H^b) from basis vector in Table I resulting in (14) and (15). The channel fading environments are simulated by changing the conditions of angle spreads at transmitter and receiver. Four cases are considered as (i) 60° spread at transmitter, 360° spread at receiver, (ii) 360° spread at transmitter, 60° spread at receiver, (iii) 60° spread at transmitter, 60° spread at receiver, (iv) 360° spread at transmitter, 360° spread at receiver. Note that case (iii) is equivalent to line of sight scenario and case (iv) is equivalent to Rayleigh fading channel.

Fig. 4 shows the capacity versus inter-element spacing for SNR = 10dB. The results indicate that to use angle domain processing realized by Butler matrix can improve the channel

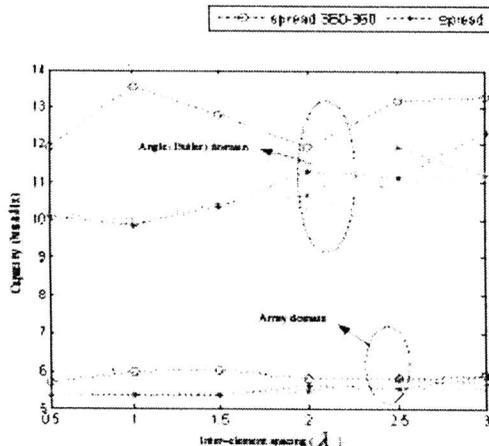


Fig.4 Capacity vs. inter-element spacing for SNR = 10dB

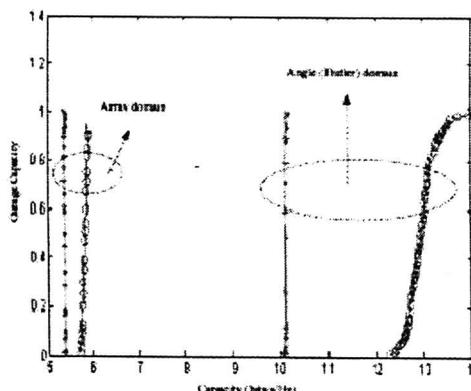


Fig.5 Outage Capacity for SNR = 10 dB.

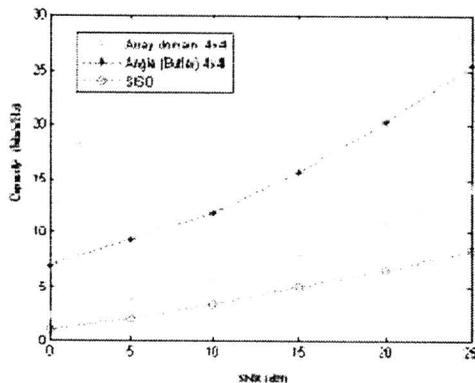


Fig.6 Capacity vs. SNR for 360-360 angle spread, $\Delta_1 = \Delta_2 = 0.5$.

capacity for any fading conditions. This is also confirmed by the outage capacity shown in Fig. 5 that the distribution of all angle domain is higher than array domain.

In Fig.6, the capacity comparison between 4x4 MIMO systems with angle domain processing, array domain processing and SISO system is presented. The MIMO systems offer better performance than SISO system and the best performance is achieved by angle domain processing.

V. CONCLUSION

This paper presents the performance of MIMO systems using angle domain processing realized by Butler matrix. The result reveals that the proposed system outperforms the conventional array domain processing for every fading cases.

It is attractive to apply Butler matrix for angular consideration on MIMO systems because of its low cost and easy to implement.

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The Enhancement of MIMO Capacity using Angle Domain Processing Based on Measured Channels

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Abstract — In this paper, the verification of using angle domain processing for Multiple Input Multiple Output (MIMO) system is presented. This paper proposes the concept of angle domain processing by applying a Butler matrix into 4x4 MIMO systems. A Butler matrix is the most attractive technique for constructing angle domain due to its low cost and easy to implement. The measured results are compared with conventional MIMO system so-called as array domain processing. The capacity performance indicates that the angle domain processing realized by Butler matrix outperforms the conventional system.

Index Terms — MIMO capacity, Array domain processing, Angle domain processing, Butler matrix.

I. INTRODUCTION

In the research area of MIMO systems, many works have been proposed to enhance the channel capacity in order to satisfy the user demand for high data rate applications. Some studies have been focused on theoretical works and some are performed by measurements. In general, most of them still develop the technique enhancing channel capacity through channel behavior [1]-[3]. It can be noticed that the common consideration of channel capacity is based on the array antennas at both transmitter and receiver. However, the channel behavior is considered by many angle parameters such as angle of arrival, angle of departure and angle spread [4]. Therefore, it is interesting to investigate the performance of MIMO systems using angle domain processing instead of conventional array domain. Recently, the authors in [5] develop the channel estimation of MIMO-OFDM system based on angle domain consideration. The applicability of angle domain technique is dependent on the channel stochastic information available to the receiver. Although the significant improvement on MIMO capacity can be expected by using angle domain processing but, so far in literature, there is no work to illustrate the capacity benefit of using angle domain processing. The reason is that the pre and post coding schemes of angle domain transformations increase the complexity on both transmitter and receiver. Hence, it challenges to find the technique with low cost and complexity matching with the concept of angle domain processing.

From simulation result, the authors investigate the advantage of using angle domain instead of array domain processing and reported in [6]. However, only simulation results cannot claim the use of proposed system. In this paper, low profile concept of angle domain processing is conveniently implemented. By only inserting Butler matrices

before antenna array at transmitter and receiver, the 4x4 MIMO system can perform as angle domain processing so the channel matrices is able to be measured. Then the channel capacity is calculated by utilizing the measured data. In addition, the capacity comparison between array domain processing and angle domain processing are given in this paper.

The paper is organized as follows. In section II, the details of both array domain and angle domain are described. Then, the feature of Butler matrix to apply for angle domain is given in section III. Section IV and V provides the measurement and simulation results of angle domain realized by Butler matrix in comparing with conventional array domain. Finally in section VI, the conclusion of this paper is given.

II. MIMO SYSTEM MODEL

A. Array domain processing

The array domain processing represent of MIMO systems. Let \mathbf{x} be a vector of the transmitted signals with N_t transmitted antennas and \mathbf{y} be a vector of the received signals with N_r received antennas. Then the relation between transmitted and received signals is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \quad (1)$$

Where \mathbf{n} is an $(N_r \times 1)$ noise vector and \mathbf{H} is an $(N_r \times N_t)$ channel matrix. With this notation channel output sequence can be written in matrix form as:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{N_r} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1N_t} \\ h_{21} & h_{22} & \dots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \dots & h_{N_rN_t} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{N_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_{N_r} \end{bmatrix} \quad (2)$$

The angle domain represent of MIMO systems. There is an arbitrary number of physical paths between the transmitter and receiver [4]; the i th path having attenuation of α_i , makes an angle of θ_i ($\Omega_{\theta_i} = \cos \theta_i$) with the transmit antenna array and an angle of ϕ_i ($\Omega_{\phi_i} = \cos \phi_i$) with the receive antenna array. The channel matrix \mathbf{H} can be written as:

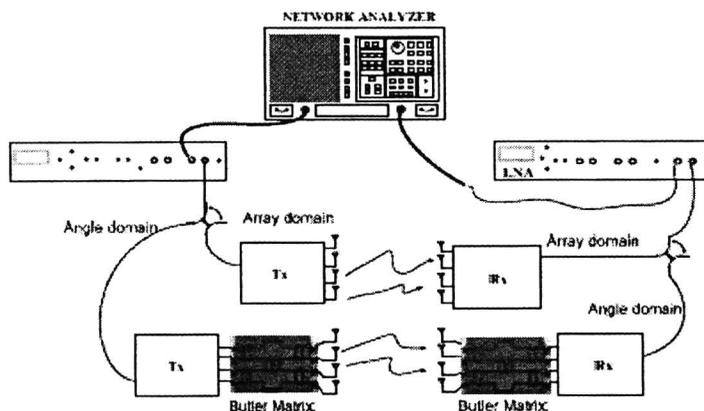


Fig. 2. A block diagram of measurement setup.

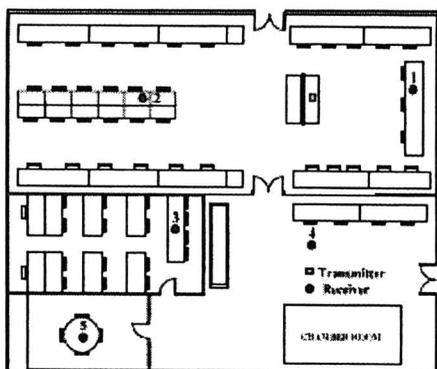


Fig. 3. Measurement scenarios.

Thus, the capacity of MIMO systems when applying Butler matrix is given by

$$C = \log_2 \det \left(\mathbf{I}_N + \frac{P}{P_s N_r} \mathbf{H}^H \mathbf{H} \right) \quad (13)$$

IV. MEASUREMENT

Fig.2 shows a block diagram of measurement set up for 4x4 MIMO system. It is clearly seen that the angle domain processing can be implemented by just inserting the Butler matrix on both transmitter and receiver. The network analyzer is used for measurement channel coefficients in magnitude and phase. The power amplifier (PA) is used at transmitter to provide more transmitted power. Low noise amplifier (LNA) is used at receiver to increase received signal level. The channel measurements are undertaken by five times at each location.

Fig.3 shows measurement scenarios. We choose a large room to provide many test locations. The location of transmitter is fixed as shown in Fig.3 with rectangular point. There are five measured locations for receiver shown

by circular point in Fig.3. It is easy to measure both array domain processing and angle domain processing by using switches presented in Fig.2. The measured results achieved by network analyzer are used as a channel response in MIMO system. Also seen in Fig.2, apart from Butler matrix, all components of array and angle domain are the same. Therefore, the measured channels can be directly compared to each other as presented in the next section.

V. RESULT AND DISCUSSIONS

The simulations are undertaken by utilizing measured data into MATLAB programming and the capacity results are evaluated by using (7) and (13). The channel matrix \mathbf{H} and \mathbf{H}^H are found by measured data from network analyzer. The channel fading environments are measured by changing the locations of receiver. Five locations are considered in Fig.3. We also assumed that, the mismatches among RF circuits in transmit/receive components and mutual coupling effects are included in the measured channel.

In Fig.4 shows comparison of array and angle domain channels of 4x4 MIMO systems at location 5, where H_{ij} is referred to the channel coefficient at i th receive antenna and j th transmit antenna. It can be observed that channels of array domain processing and angle domain processing are quite different. The amplitude deviation is about ± 5 dB and the phase deviation is about $\pm 100^\circ$. These deviations are dominant to the capacity performance of MIMO system. For other locations, the deviations of amplitude and phase are similar to location 5.

In Fig.5, the average capacity versus signal to noise ratio (SNR) at each location is presented. The results indicate that to use the angle domain processing realized by Butler matrix offers better performance than array domain processing. In order to justify the results, the numeric values of average capacity at SNR = 10 dB are given in Table II.

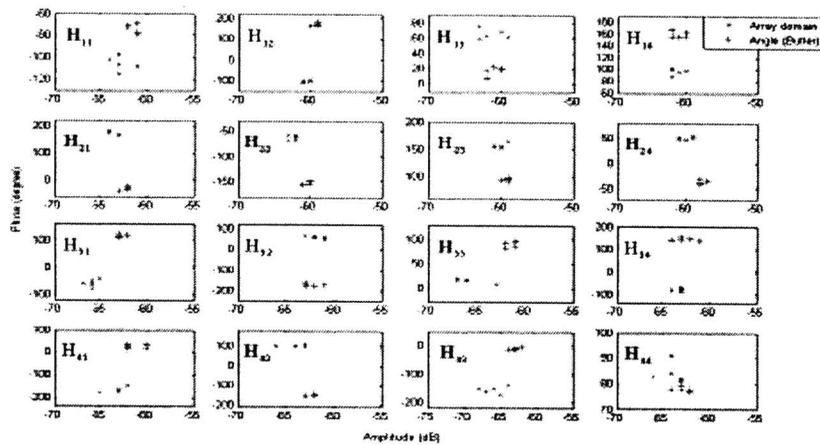


Fig. 4. Measured 4x4 MIMO channels of array domain processing and angle domain processing (Butler matrix), at location 5.

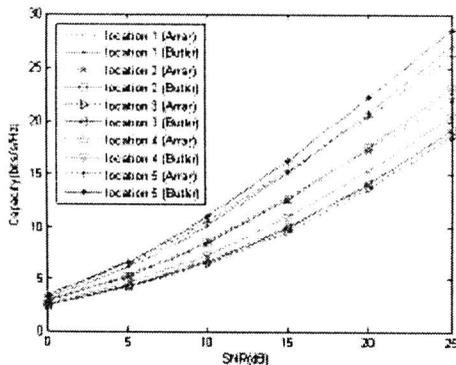


Fig. 5. The average capacity vs. SNR at each location.

It is noticed that the benefit of angle domain processing is more pronounced at location 1 and 5. The reason is that these locations are close to wall and there are many surrounding furniture providing more multipath. However, the improvement of MIMO capacity can be observed from all locations.

VI. CONCLUSION

This paper verifies the benefit of using angle domain processing for 4x4 MIMO systems by measured results. The angle domain processing realized by Butler matrix is implemented and compared with array domain processing. The results reveal that the angle domain processing outperforms the conventional array domain processing for all fading locations. Hence, the proposed system is attractive to practically implement on MIMO systems due to its ease and low complexity.

TABLE II
AVERAGE CAPACITY COMPARISONS BETWEEN ARRAY DOMAIN AND ANGLE DOMAIN FOR SNR = 10

Location	Average capacity (bits/s/Hz)	
	Array domain	Angle domain (Butler)
1	8.72	10.12
2	8.43	8.52
3	6.46	6.65
4	6.88	7.37
5	10.57	11.03

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ประวัติผู้วิจัย

ผู้ช่วยศาสตราจารย์ ดร. พีระพงษ์ อุฑารสกุล สำเร็จการศึกษาหลักสูตรวิศวกรรมศาสตรบัณฑิต และวิศวกรรมศาสตรมหาบัณฑิตจากจุฬาลงกรณ์มหาวิทยาลัย เมื่อ พ.ศ. 2539 และ 2541 จากนั้นเข้าทำงานในตำแหน่งวิศวกรระบบโทรคมนาคมที่องค์การโทรศัพท์แห่งประเทศไทย จนกระทั่ง พ.ศ. 2543 จึงได้ย้ายมาเป็นอาจารย์ประจำสาขาวิชาวิศวกรรมโทรคมนาคม สำนักวิชาวิศวกรรมศาสตร์ มหาวิทยาลัยเทคโนโลยีสุรนารี และได้ลาศึกษาต่อระดับปริญญาเอกตั้งแต่ปี พ.ศ. 2546 ณ University of Queensland, Australia เมื่อ พ.ศ. 2549 จึงได้กลับเข้ามาปฏิบัติหน้าที่อาจารย์ตามเดิม ผู้วิจัยมีเชี่ยวชาญในด้านระบบ MIMO, Information Theory, Signal Processing, Radio Wave Modelling, Mobile Communication, Advance Wireless Communication ปัจจุบันมีบทความวิจัยตีพิมพ์เผยแพร่ในวารสารวิชาการ 21 บทความ และในการประชุมวิชาการ 60 บทความ หนังสือวิชาการในประเทศ 1 เล่มและต่างประเทศ 1 เล่ม มีลิขสิทธิ์ 1 รายการและ สิทธิบัตร 1 รายการ

ผู้ช่วยศาสตราจารย์ ดร. พีระพงษ์ อุฑารสกุล ได้รับรางวัล Young Scientist Travel Grant Award จากงานประชุมวิชาการนานาชาติ International Symposium on Antenna Propagation ปี พ.ศ. 2547 ณ ประเทศญี่ปุ่น และได้รับรางวัล Best Student Presentation Award จากงานประชุมวิชาการนานาชาติ Australian Symposium on Antennas ปี พ.ศ. 2548 ณ ประเทศออสเตรเลีย ในปี พ.ศ. 2553 ผู้ช่วยศาสตราจารย์ ดร. พีระพงษ์ อุฑารสกุล ได้รับรางวัลพนักงานดีเด่น ด้านการวิจัย สำหรับนักวิจัยรุ่นใหม่ จากมหาวิทยาลัยเทคโนโลยีสุรนารี

