Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2012, Article ID 638150, 10 pages
doi:10.1155/2012/638150

Research Article

Angular Beamforming Technique for MIMO Beamforming System

Apinya Innok, Peerapong Uthansakul, and Monthippa Uthansakul

School of Telecommunication Engineering, Suranaree University of Technology, Muang, Nakhon Ratchasima 30000, Thailand

Correspondence should be addressed to Apinya Innok, apinya_in@hotmail.com

Received 3 August 2012; Revised 2 October 2012; Accepted 6 November 2012

Academic Editor: Ananda Sanagavarapu Mohan

The method of MIMO beamforming has gained a lot of attention. The eigen beamforming (EB) technique provides the best performance but requiring full channel information. However, it is impossible to fully acquire the channel in a real fading environment. To overcome the limitations of the EB technique, the quantized beamforming (QB) technique was proposed by using only some feedback bits instead of full channel information to calculate the suitable beamforming vectors. Unfortunaely, the complexity of finding the beamforming vectors is the limitation of the QB technique. In this paper, we propose a new technique named as angular beamforming (AB) to overcome drawbacks of QB technique. The proposed technique offers low computational complexity for finding the suitable beamforming vectors. In this paper, we also present the feasibility implementation of the proposed AB method. The experiments are undertaken mainly to verify the concept of the AB technique by utilizing the Butler matrix as a two-bit AB processor. The experimental implementation and the results demonstrate that the proposed technique is attractive from the point of view of easy implementation without much computational complexity and low cost.

1. Introduction

The multiple input multiple output (MIMO) systems provide a good quality of service such as channel capacity. In general, for MIMO systems, the consideration of channel capacity is based on the use of array antennas at both the transmitter and the receiver. Many works have proposed the eigen beamforming (EB) technique in the literature [1–5]. This technique utilizes the properties of estimated channels by performing singular value decomposition on channel matrix. Then the eigenvectors of the channel matrix are considered as pre- and postcoding schemes for MIMO systems. This technique can improve the capacity performance, but both transmitter and receiver have to have perfect knowledge of the channel information. However, there are many issues that make use of EB technique in practice such as a requirement of high system complexity and many procedures employed for channel feedback transmission. In this paper, we propose a new technique known as angular beamforming (AB) technique; the received channels are used to estimate the suitable pre- and postcoding schemes at the receiver side. Then, a little number of bits are fed back to transmitter in order to form beam to the suitable direction according to the channel. The pre- and postcoding schemes are low complexity and offer high channel capacity. Therefore, the study of using AB technique is the focus of this paper.

Many works on MIMO system [6–9] have been proposed to enhance the channel capacity in order to satisfy the user demand for high data rate applications. Some of the studies were focused on theoretical works, and others performed measurements. Nevertheless, most of the paper developed techniques to enhance the channel capacity through channel behaviour [10–12] such as adjusting transmitted powers according to eigenvalue of channels which is known as water filling method. In general, it can be noticed that the theoretical consideration of channel capacity is based on the assumption that array antennas are employed at both the transmitter and the receiver. However, the channel characteristic is dependent on many angle-based parameters of multipath such as angle of arrival, angle of departure, and angle of spread. Therefore, it would be interesting to investigate the performance of MIMO system using the angular beamforming (AB) instead of the conventional methods.

Recently, the authors in [13, 14] developed a channel estimation of MIMO-OFDM system based on angular beamforming (AB) consideration. The applicability of AB technique depends on the channel stochastic information available at the receiver. The design of suitable pilots is proposed by facilitating the direct implementation of analyzing the performances of different channel estimation techniques. Although the significant improvement on MIMO capacity can be expected by using AB method, so far in the literature, there is no work available that illustrates the capacity benefit of using AB method. The reason is the lack of pre- and post-coding schemes for angle transformations that can decrease the complexity on both transmitter and receiver. Hence, it is challenging to find a technique that can obtain lower cost and lower complexity that matches with the concept of AB method. In [15], a scheme was proposed that uses a discrete fourier transformation (DFT) to receive a signal vector in RF domain. This can be realized by placing a Butler matrix between the antenna elements and the receiver switch. However, [15] presented only the simulations results, and no measurement result was provided. With only simulation results, one cannot claim the practical advantages of the system. A low profile concept of angle domain processing has been conveniently implemented in [16] by only inserting Butler matrices before antenna array at transmitter and receiver. The authors of [17] investigated the correlation coefficients (line of sight and nonline of sight) via both simulation and measurement results. However, they did not discuss any analysis of correlation coefficients which was later presented by us in [18]. But, in our previous work, we did not consider the process of feedback bits for increasing channel capacity. In this paper, the complexity analysis of how Angular beamforming (AB) and quantized beamforming (QB) impact on the channel matrix is provided. We also provide reasons as to why the use of AB method for MIMO system offers a better performance over a QB method. Further, in this paper, we perform experimental campaigns by fabricating a Butler matrix so as to further demonstrate the usefulness of our system for practical application. The Butler matrix was chosen because it is just a low-complexity hardware that can offer the Angular beamforming (AB). In general, there are infinite choices to choose for the set of orthogonal steering vectors to form an AB. Therefore, it is hard to justify whether Butler matrix provides the best performance among others. To focus on hardware complexity, the other methods to form AB might need 16 phase shifters to simultaneously form 4 beams whereas the Butler matrix approach uses only one low-cost printed circuit board. This motivated the authors to construct the 4×4 MIMO system featuring AB by employing a Butler matrix which has a low profile concept and is convenient for implementation. This Butler matrix simultaneously forms multiple beams for providing departure or arrival angles into four directions. By only inserting Butler matrix into the antenna arrays, the conventional MIMO systems can be transformed into the MIMO systems with Angular beamforming (AB) without the need for additional burden on processing units at both transmitter and receiver.

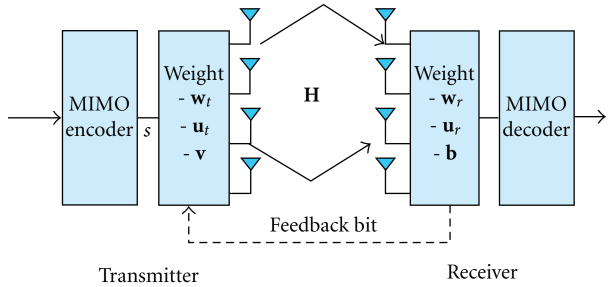


Figure 1: 4×4 MIMO system with beamforming.

In summary, the contribution of this paper falls into three main categories. The first contribution is related to the comparisons in terms of channel capacity. Secondly, we demonstrate as to how the simulation complexity of AB method and QB method impacts on the channel matrix which is not available elsewhere. The main aim here is to help the reader to understand the key benefits offered by AB. The third contribution is to the implementation feasibility of AB method for 4×4 MIMO systems which has been demonstrated using a Butler matrix. All the three contributions either propose a new concept or confirm the actual benefit of employing MIMO with AB. The paper is organized as follows. In Section 2, the details of MIMO beamforming, AB, QB, and EB techniques are described. Then in Section 3, the simulation results and complexity analysis of using AB and QB are explained. The implementation and feasibility of using a Butler matrix to apply for AB are given in Section 4. Section 5 describes the details of channel measurements. Section 5 provides the measurement results of AB realized by Butler matrix in comparing with CM system. Finally in Section 6, the conclusion of this paper is given.

2. MIMO Beamforming

2.1. Angular Beamforming (AB). Referring to Figure 1, the transmitter, the data symbol s is modulated by the beamformer $\mathbf{u}_t$, and then the signals are transmitted into a MIMO channel. At the receiver, the signals are processed with the beamforming vector $\mathbf{u}_r$. Then the relation between transmitted and received signal is given by

$$y = \mathbf{u}_r^* [\mathbf{H}\mathbf{u}_t s + \mathbf{n}]. \tag{1}$$

The transmit beamforming vector $\mathbf{u}_t$ and the receive beamforming vector $\mathbf{u}_r$ in (1) are usually chosen to maximize the receive SNR. Without loss of generality, we assume that $\|\mathbf{U}_r\|^2 = 1$, $E\{\|s\|^2\} = 1$. Then the received SNR is expressed as

$$\rho = \frac{E\left\{||\mathbf{u}_r^* \mathbf{H}\mathbf{u}_t s||^2\right\}}{E\left\{||\mathbf{u}_r^* \mathbf{n}||^2\right\}} = \frac{||\mathbf{u}_r^* \mathbf{H}\mathbf{u}_t||^2}{\sigma_n^2}. \tag{2}$$

To maximize the received SNR, the optimal transmit beamformer is chosen as the eigenvector corresponding to the largest eigen-value of $\mathbf{HH}^*$. The singular values can be obtained form SVD technique by using MATLAB. Thus the maximized received SNR is $\rho = (\lambda_{\max}(\mathbf{HH}^*))/(\sigma_n^2)$. The $\lambda_{\max}$ is the maximum eigen-value of a matrix that is formed by identically distributed (i.i.d.) complex Gaussian random variables with zero-mean and variance σ_n^2 in [3].

There is an arbitrary number of physical paths between the transmitter and receiver [19]; the ith path having attenuation of a_i makes an angle of ϕ_{ti} ($\Omega_{ti} := \cos\phi_{ti}$) with the transmit antenna array and angle of ϕ_{ri} ($\Omega_{ri} := \cos\phi_{ri}$) with the receive antenna array. The channel matrix $\mathbf{H}$ can be written using the following expressions:

$$\mathbf{H} = \sum_i a_i^b \mathbf{e}_r(\Omega_{ri})\mathbf{e}_t(\Omega_{ti})^*, \tag{3}$$

where

$$a_i^b := a_i\sqrt{N_t N_r}\exp\left(-\frac{j2\pi d_i}{\lambda_c}\right),$$

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

$$\mathbf{e}_r(\Omega) := \frac{1}{\sqrt{N_r}}\begin{bmatrix} 1 \\ \exp[-j(2\pi\Delta_r\Omega)] \\ \vdots \\ \exp[-j(N_r-1)(2\pi\Delta_r\Omega)] \end{bmatrix}. \tag{4}$$

Also, d_i is the distance between transmit and receive antennas along ith path. Note that $(\cdot)^*$ is the conjugate and transpose operation. The vectors $\mathbf{e}_t$ (Ω) and $\mathbf{e}_r$ (Ω) are, respectively, transmitted and received unit spatial signatures along the direction Ω, and λ_c is the wavelength of the center frequency in a whole signal bandwidth. Assuming uniform linear array, the normalized separation between the transmit antennas is Δ_t (antenna separation/λ_c), and the normalized separation between receive antennas is Δ_r (antenna separation/λ_c). Note that the reason of normalization is because this proposed system can work in any frequency band. Hence, the normalization is made to neglect the unused parameter. Channel state information (CSI) is not available at the transmitter. The concept of Angular beamforming (AB) can be represented by the transmitted and received signals. It is convenient for implementation by just inserting $\mathbf{u}_t$ and $\mathbf{u}_r$ at both transmitter and receiver because the beamforming vectors depend on angle of arrival or departure. The numbers of feedback bits are defined by the angle (θ), $\theta \in [0,\pi)$. The angles are divided equally. The angle can be expressed as $N_i = 2^{B_i}$, N_i denoting the number of angle levels. B_i is the number of feedback bits. When comparing with Quantized Beamforming (QB), the procedure to find beamforming vectors in QB is more complex than that of AB. The detail of QB is shown in the next section. In general, $\mathbf{u}_t$ and $\mathbf{u}_r$ can be written as

$$\begin{aligned} \mathbf{u}_t &= \frac{1}{\sqrt{N_t}}\exp(jlk\Delta_t\cos\theta); \quad l = 1,2,\ldots,N_t, \\ \mathbf{u}_r &= \frac{1}{\sqrt{N_r}}\exp(jmk\Delta_r\cos\theta); \quad m = 1,2,\ldots,N_r, \end{aligned} \tag{5}$$

where $k = 2\pi/\lambda_c$. We can use $\max\|\mathbf{u}_r^*\mathbf{H}\mathbf{u}_t\|^2$ that will be maximum for $\mathbf{u}_t$ and $\mathbf{u}_r$. So the channel matrix of AB can be written as

$$\mathbf{H}_{\max}^a = \mathbf{u}_{r\max}^*\mathbf{H}\mathbf{u}_{t\max}. \tag{6}$$

Thus, the capacity [20] of MIMO systems using AB is given by

$$C = \log_2\det\left(\mathbf{I}_{N_r} + \frac{P_t}{P_N N_t}\mathbf{H}_{\max}^a\mathbf{H}_{\max}^{a\,*}\right), \tag{7}$$

where P_t is the transmitted power and P_N is the noise power in each branch of antennas at the receiver. Note that the signal-to-noise power ratio (SNR) is defined as P_t/P_N. $\mathbf{I}_{N_r}$ is the identity matrix having $N_r \times N_r$ dimension, and $\mathbf{H}$ is the channel matrix having $N_r \times N_t$ dimension with $\mathbf{H}^*$ being its transpose conjugate. In this paper, the channel matrix $\mathbf{H}$ is normalized by $\|\mathbf{H}\|_F^2 = N_r N_t$. $\mathbf{H}_{\max}^a$ is the channel matrix of size $N_r \times N_t$ streams.

2.2. Quantized Beamforming (QB). In eigen beamforming (EB) designs, we have assumed that the transmitter has perfect knowledge of CSI. However, in many real systems, having the CSI known exactly at the transmitter is hardly possible. The channel information is usually provided by the receiver through a bandwidth-limited finite-rate feedback channel, and quantization method, which has been widely studied for source coding [3], can be used to provide the feedback information. We assume herein that the receiver has perfect CSI. The transmit beamforming vector $\mathbf{w}_t$ for QB is used under the uniform elemental power constraint. The expression for transmit beamformer $\mathbf{w}_t(\theta_0,\theta_1,\ldots,\theta_{N_t-1})$ which is a function of N_t parameters $\{\theta_i,\ \theta_i \in [0,2\pi)\}_{i=0}^{N_t-1}$ is obtained using simple manipulations as

$$\mathbf{w}_t(\theta_0,\theta_1,\ldots,\theta_{N_t-1}) = \frac{1}{\sqrt{N_t}}e^{j\theta_0}\begin{bmatrix} 1 \\ e^{j\ddot{\theta}_1} \\ \vdots \\ e^{j\ddot{\theta}_{N_t-1}} \end{bmatrix}, \tag{8}$$

where $\|\mathbf{H}\mathbf{w}_t(\theta_0,\theta_1,\ldots,\theta_{N_t-1})\|^2 = \|\mathbf{H}\mathbf{w}_t(\ddot{\theta}_1,\ddot{\theta}_2,\ldots,\ddot{\theta}_{N_t-1})\|^2$. Since $\|\mathbf{H}\mathbf{w}_t(\theta_0,\theta_1,\ldots,\theta_{N_t-1})\|^2 = \|\mathbf{H}\mathbf{w}_t(\ddot{\theta}_1,\ddot{\theta}_2,\ldots,\ddot{\theta}_{N_t-1})\|^2$. We can reduce one parameter and quantize $\mathbf{w}_t(\ddot{\theta}_1,\ddot{\theta}_2,\ldots,\ddot{\theta}_{N_t-1})$ instead of $\mathbf{w}_t(\theta_0,\theta_1,\ldots,\theta_{N_t-1})$. Consider

$$\mathbf{w}_t\left(\ddot{\theta}_1^{n_i},\ldots,\theta_{N_t-1}^{n_{N_t-1}}\right) = \frac{1}{\sqrt{N_t}}\begin{bmatrix} 1 \\ e^{j\ddot{\theta}_1^{n_1}} \\ \vdots \\ e^{j\ddot{\theta}_{N_t-1}^{n_{N_t-1}}} \end{bmatrix}, \tag{9}$$

Table 1: Average capacity (bps/Hz) 4×4 MIMO beamforming for SNR = 10 dB.

Methods	Number of feedback bits							
	1	2	3	4	5	6	7	8
EB	5.113	5.113	5.113	5.113	5.113	5.113	5.113	5.113
AB	2.391	4.538	5.076	5.088	5.091	5.093	5.093	5.093
QB	3.711	3.711	5.09	5.09	5.09	5.09	5.09	5.09

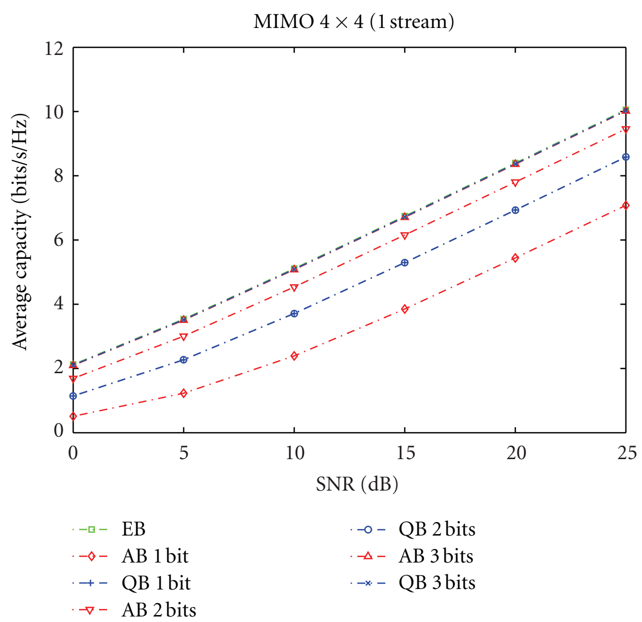


Figure 2: Capacity versus SNR.

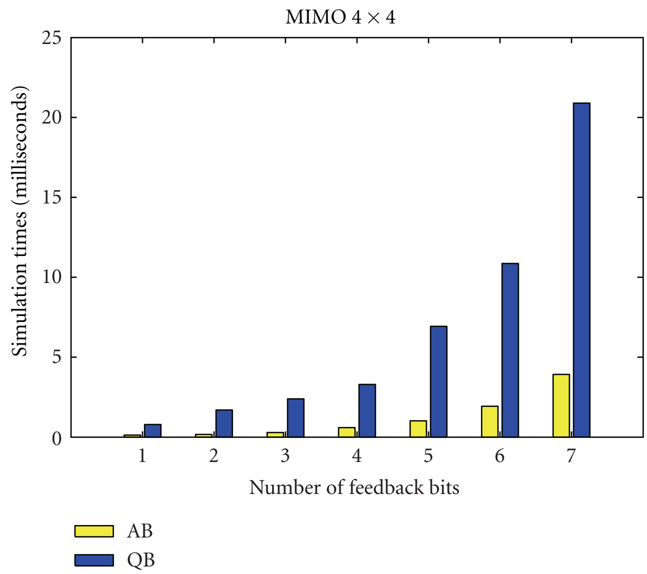


Figure 3: Simulation times versus number of feedback bits.

where $\ddot{\theta}_1^{n_i} = (2\pi n_i)/(N_i)$, $0 \le n_i \le N_i - 1$, $i = 1, 2, \ldots, N_t - 1$, with $N_i = 2^{B_i}$ and N_i denoting the number of quantization levels and feedback index of $\ddot{\theta}$, respectively, and where B_i is the number of feedback bits for $\ddot{\theta}_i$.

We quantize the parameters $\ddot{\theta}_i$ to the round-off grid point $\ddot{\theta}_1^{n_i}$, $i = 1, 2, \ldots, N_t - 1$. Hence for this quantization scheme, we need to send the index set n_i from the receiver to the transmitter. Let $\mathbf{w}_t$ and $\mathbf{w}_r$ be the beamforming vectors. This requires $B = \sum_{i=1}^{N_t-1} B_i$ bits. The receive beamformer $\mathbf{w}_r$ can be written as

$$\mathbf{w}_r = \frac{\mathbf{H}\mathbf{w}_t\left(\ddot{\theta}_1^{n_i}, \ddot{\theta}_2^{n_i}, \ldots, \theta_{N_t-1}^{n_{N_t-1}}\right)}{\left\|\mathbf{H}\mathbf{w}_t\left(\ddot{\theta}_1^{n_i}, \ddot{\theta}_2^{n_i}, \ldots, \theta_{N_t-1}^{n_{N_t-1}}\right)\right\|}. \tag{10}$$

We can use $\max \|\mathbf{w}_r^* \mathbf{H} \mathbf{w}_t\|^2$ that will provide maximum $\mathbf{w}_t$ and $\mathbf{w}_r$. Then, the channel matrix QB when applying the maximum transmits beamforming $(\mathbf{w}_{t\max})$ and the maximum receive combing vector $(\mathbf{w}_{r\max})$ can be written as

$$\mathbf{H}_{\max}^q = \mathbf{w}_{r\max}^* \mathbf{H} \mathbf{w}_{t\max}. \tag{11}$$

Thus, the capacity [20] of MIMO system using QB is given by

$$C = \log_2 \det\left(\mathbf{I}_{N_r} + \frac{P_t}{P_N N_t} \mathbf{H}_{\max}^q \mathbf{H}_{\max}^{q\,*}\right), \tag{12}$$

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

2.3. Eigen Beamforming (EB). Considering a MIMO channel with $N_r \times N_t$ channel matrix $\mathbf{H}$ to be known at both the transmitter and the receiver, the eigenvectors can be found by applying SVD technique to the channel matrix as shown in the following:

$$\mathbf{H} = \mathbf{B}\mathbf{S}\mathbf{V}^*, \tag{13}$$

where $N_r \times N_r$ matrix $\mathbf{B}$ and the $N_t \times N_t$ matrix $\mathbf{V}$ are unitary matrices and $\mathbf{S}$ is an $N_r \times N_t$ diagonal matrix. The beamforming vectors $\mathbf{b}$ and $\mathbf{v}$ can be found from unitary matrices $\mathbf{B}$ and $\mathbf{V}$, respectively. The beamforming vectors are given by the first column of the unitary matrices. These two vectors are used as pre- and postcoding matrices at transmitter and receiver, respectively. So the channel matrix of EB can be written as

$$\mathbf{H}^e = \mathbf{b}^* \mathbf{H} \mathbf{v}. \tag{14}$$

Thus, the capacity of MIMO system using EB is given by

$$C = \log_2 \det\left(\mathbf{I}_{N_r} + \frac{P_t}{P_N N_t} \mathbf{H}^e \mathbf{H}^{e*}\right). \tag{15}$$

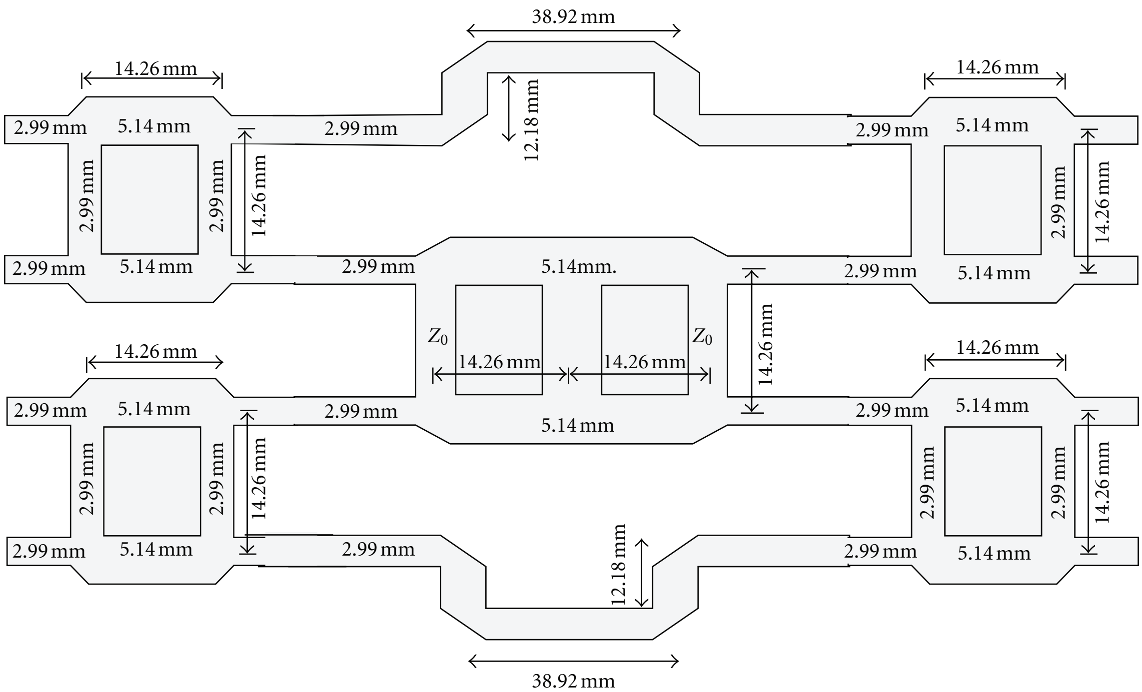


Figure 4: The dimensions of Butler matrix.

Table 2: The process of formation of FLOP with the QB.

QB	FLOP
$N_i = 2^{B_i}$	$B - 1$
$B_{a_1} = \lfloor B/(N_t - 1) \rfloor$	2
$B_{a_2} = B_{a_1} + 1$	1
$N_s = B - B_{a_1}(N_t - 1)$	3
$\ddot{\theta}_i = \dfrac{2\pi n_i}{N_i};\ 0 \le n_i \le N_i - 1$	2
Return loop $\theta_i^{n_i}$ can find from N_i	$B - 1$
$\mathbf{w}_t\left(\ddot{\theta}_1^{n_i}, \ldots, \theta_{N_{t-1}}^{n_{N_t-1}}\right) = \dfrac{1}{\sqrt{N_t}}\begin{bmatrix} 1 \\ e^{j\ddot{\theta}_1^{n_1}} \\ \vdots \\ e^{j\ddot{\theta}_{N_t-1}^{n_{N_t-1}}} \end{bmatrix}$	$N_t - 1$
$\mathbf{w}_r = \dfrac{\mathbf{H}\mathbf{w}_t\left(\ddot{\theta}_1^{n_i}, \ddot{\theta}_2^{n_i}, \ldots, \theta_{N_{t-1}}^{n_{N_t-1}}\right)}{\left\Vert \mathbf{H}\mathbf{w}_t\left(\ddot{\theta}_1^{n_i}, \ddot{\theta}_2^{n_i}, \ldots, \theta_{N_{t-1}}^{n_{N_t-1}}\right)\right\Vert}$	$3(N_t - 1)$
$h_s = \dfrac{1}{\sqrt{N_t}} \Vert \mathbf{w}_r^* \mathbf{H}\mathbf{w}_t \Vert^2$	5
Return loop and find maximum channel from $N_i = 2^{B_i}$	$B - 1$
Total	$2B^2 + 5B + 4BN_t - 4N_t - 7$

3. Simulation Results and Discussion

The simulations are performed using MATLAB, and the capacity results are evaluated by using (7), (12), and (15).

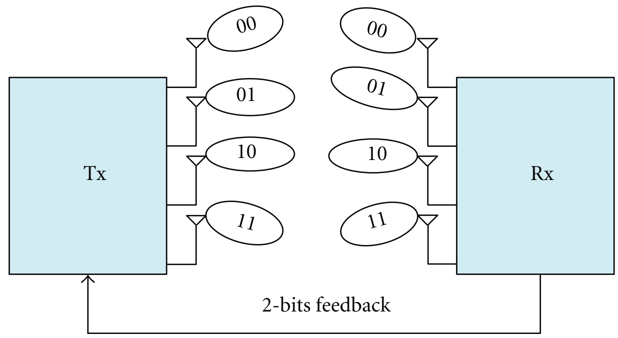


Figure 5: Illustration of applying two-bit feedback (Butler matrix) for 4×4 MIMO systems.

Figure 2 shows the average capacity versus SNR. We increase the number of feedback bits, since the range of capacity enhancement depends on the number of feedback bits. Also, the number of feedback bits can improve the channel capacity. The numerical values of average capacity at SNR = 10 dB for other bits are given in Table 1. It can be obviously noticed that the benefit of AB is pronounced for all the bits. It must be kept in mind that the improvement of MIMO capacity comes with a cost of inserting $\mathbf{u}_t$ and $\mathbf{u}_r$ at both transmitter and receiver and corresponding extra implementation complexity. The optimum EB offers better performance than both QB and AB. However, the implementation of AB is so easy that provides a very good tradeoff with EB.

The method of calculating feedback bits in AB is simpler than QB so that the operating time of AB is much shorter

Table 3: The process of formation of FLOP with the AB.

AB	FLOP
$N_i = 2^{B_i}$	$B-1$
$\pi/2^B$	1
Return loop find θ from N_i	$B-1$
$\mathbf{u}_t = (1/\sqrt{N_t})\exp(jlk\Delta_t\cos\theta);\ l=1,2,\ldots,N_t$	N_t
$\mathbf{u}_r = (1/\sqrt{N_r})\exp(jlk\Delta_r\cos\theta);\ l=1,2,\ldots,N_r$	N_r
$h_a = (1/N_t)\lVert\mathbf{u}_r^*\mathbf{H}\mathbf{u}_t\rVert^2$	5
Return loop and find maximum channel from $N_i = 2^{B_i}$	$B-1$
Total	$2B^2+2B+BN_t+BN_r-N_t-N_r-4$

Table 4: Element phasing, beam direction, and interelement phasing for the Butler matrix shown in Figure 3 (conceptual).

$\mathbf{b}_t, \mathbf{b}_r$	$E1\ (l=1)$	$E2\ (l=2)$	$E3\ (l=3)$	$E4\ (l=4)$	Beam direction	Interelement phasing
Port 1 ($m=1$)	$\frac{1}{\sqrt{4}}e^{-j45^\circ}$	$\frac{1}{\sqrt{4}}e^{-j180^\circ}$	$\frac{1}{\sqrt{4}}e^{j45^\circ}$	$\frac{1}{\sqrt{4}}e^{-j90^\circ}$	138.6°	−135°
Port 2 ($m=2$)	$\frac{1}{\sqrt{4}}e^{j0^\circ}$	$\frac{1}{\sqrt{4}}e^{-j45^\circ}$	$\frac{1}{\sqrt{4}}e^{-j90^\circ}$	$\frac{1}{\sqrt{4}}e^{-j135^\circ}$	104.5°	−45°
Port 3 ($m=3$)	$\frac{1}{\sqrt{4}}e^{-j135^\circ}$	$\frac{1}{\sqrt{4}}e^{-j90^\circ}$	$\frac{1}{\sqrt{4}}e^{-j45^\circ}$	$\frac{1}{\sqrt{4}}e^{-j0^\circ}$	75.5°	45°
Port 4 ($m=4$)	$\frac{1}{\sqrt{4}}e^{-j90^\circ}$	$\frac{1}{\sqrt{4}}e^{j45^\circ}$	$\frac{1}{\sqrt{4}}e^{-j180^\circ}$	$\frac{1}{\sqrt{4}}e^{-j45^\circ}$	41.4°	135°

Table 5: Element phasing, beam direction, and interelement phasing for the Butler matrix shown in Figure 4 (manufactured).

$\mathbf{b}_t, \mathbf{b}_r$	E1 ($l=1$)	E2 ($l=2$)	E3 ($l=3$)	E4 ($l=4$)	Beam direction	Interelement phasing (average)
Port 1 ($m=1$)	$\frac{1}{\sqrt{4}}e^{j158^\circ}$	$\frac{1}{\sqrt{4}}e^{j25^\circ}$	$\frac{1}{\sqrt{4}}e^{-j112^\circ}$	$\frac{1}{\sqrt{4}}e^{j118^\circ}$	138°	−130°
Port 2 ($m=2$)	$\frac{1}{\sqrt{4}}e^{-j87^\circ}$	$\frac{1}{\sqrt{4}}e^{-j137^\circ}$	$\frac{1}{\sqrt{4}}e^{j176^\circ}$	$\frac{1}{\sqrt{4}}e^{j137^\circ}$	105°	−42°
Port 3 ($m=3$)	$\frac{1}{\sqrt{4}}e^{j132^\circ}$	$\frac{1}{\sqrt{4}}e^{j178^\circ}$	$\frac{1}{\sqrt{4}}e^{-j139^\circ}$	$\frac{1}{\sqrt{4}}e^{-j98^\circ}$	76°	50°
Port 4 ($m=4$)	$\frac{1}{\sqrt{4}}e^{j136^\circ}$	$\frac{1}{\sqrt{4}}e^{-j90^\circ}$	$\frac{1}{\sqrt{4}}e^{j40^\circ}$	$\frac{1}{\sqrt{4}}e^{j176^\circ}$	42°	138°

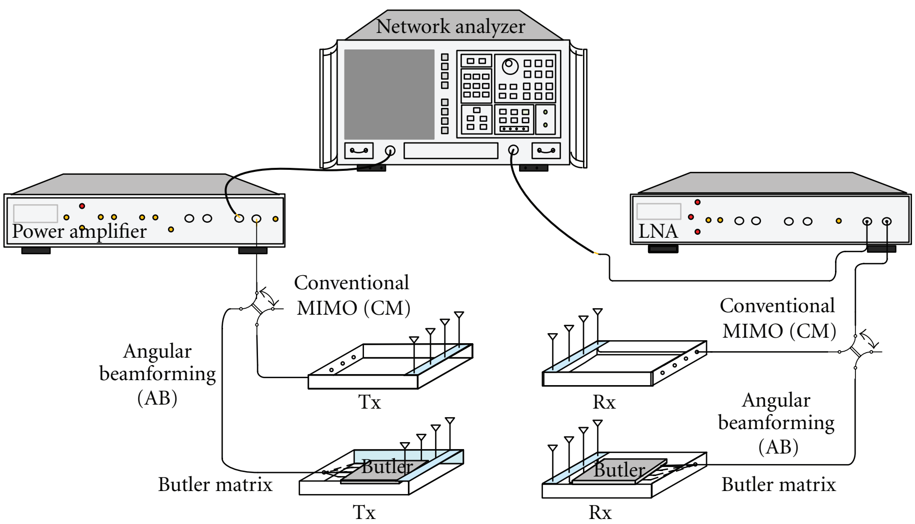


Figure 6: Block diagram of measurement setup.

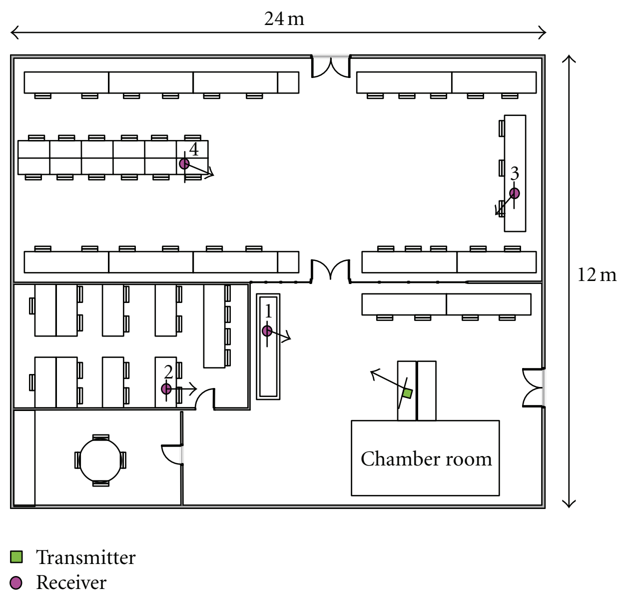


Figure 7: Measurement scenarios.

than QB. The complexity of QB and AB can be expressed in Tables 2 and 3, respectively. We evaluate the complexity [21] of AB and QB in terms of FLOPs. It is clearly seen that the Flop in Table 3 of AB is less than Flop of QB presented in Table 2. This implies that the lower processing time for AB can be obtained, which is shown in Figure 3. Figure 3 also shows the time spent computation with feedback information for 4×4 MIMO beamforming. The simulation times versus number of feedback bits using AB and QB technique are presented. It is demonstrated that AB requires less processing time than QB.

4. Feasibility of Practical Implementation

The feasibility of implementing AB processing for 4×4 MIMO systems is explored here by using Butler matrix [22]. Butler matrix constitutes four 90° hybrid couplers and two phase shifters with 45° phase and a crossover. Figure 4 shows the dimensions of Butler matrix which has been calculated by using transmission line theory. The fixed beamforming matrix is a bidirectional transmission. Hence, it can be used for either receiver or transmitter.

It can be easily shown that the weight vectors corresponding to each port presented in Table 4 are mutually orthogonal. Therefore, instead of using (5), the vector beamforming of applying Butler matrix can be written by the following expressions:

$$\begin{aligned} \mathbf{b}_t &= \frac{1}{\sqrt{N_t}} \exp(jlk\Delta_t \cos\phi); \quad l = 1, 2, \ldots, N_t, \\ \mathbf{b}_r &= \frac{1}{\sqrt{N_r}} \exp(jmk\Delta_t \cos\phi); \quad m = 1, 2, \ldots, N_r, \end{aligned} \tag{16}$$

where ϕ is the beam direction in Table 5. The characteristic of fabricated prototype is also confirmed by measuring interelement phasing and beam direction which are shown in Table 5. In this table, the distributions of all interelement phasing are similar to conceptual Butler matrix but they are slightly deviated by ± 10 degree. However, the beam direction is deviated only by just 0.6 degree.

Figure 5 illustrates the beam direction of applying 2-bit feedback (Butler matrix) to both transmitter and receiver. It is interesting to see that the concept of AB is successfully achieved by simply adding Butler matrices next to antenna elements. We use the beamforming vector $\mathbf{b}_{t_1}$ representing beam direction 00; $\mathbf{b}_{t_2}$, $\mathbf{b}_{t_3}$, and $\mathbf{b}_{t_4}$ represent beam direction 01, 10, and 11 degrees, respectively. Then, the channel matrix realized by Butler matrix can be written as

$$\mathbf{H}^b = \mathbf{b}_r^* \mathbf{H} \mathbf{b}_t, \tag{17}$$

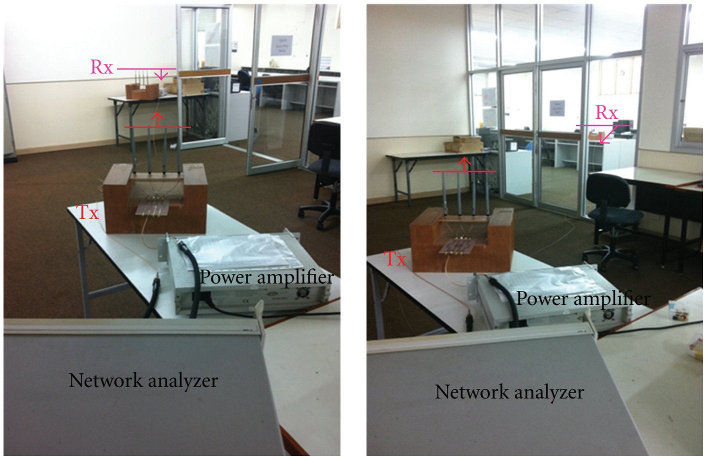
where $\mathbf{b}_t$ and $\mathbf{b}_r$ are the beamforming vectors whose rows are the vectors in four directions for transmitter and receiver and $\mathbf{H}$ is channel matrix of size $N_r \times N_t$ to get conventional MIMO. Thus, the capacity of MIMO systems when applying Butler matrix is given by

$$C = \log_2 \det\left(\mathbf{I}_{N_r} + \frac{P_t}{P_N N_t} \mathbf{H}^b \mathbf{H}^{b*}\right). \tag{18}$$

5. Measurement Results and Discussion

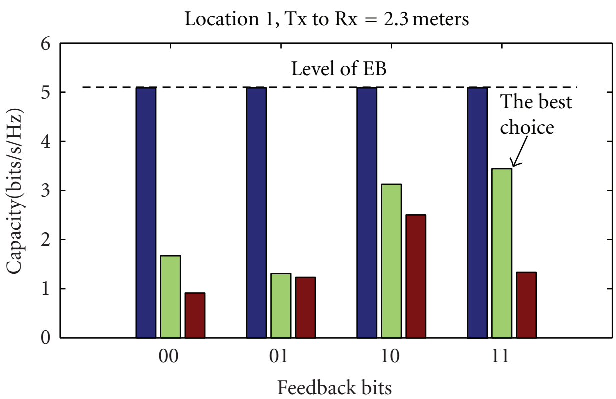
Figure 6 shows a block diagram of measurement setup for 4×4 MIMO system. The network analyzer is used for measuring channel coefficients in magnitude and phase. The power amplifier (PA) is used at transmitter to provide more transmitted power. Low noise amplifier (LNA) is used at the receiver to increase the appropriate by the received signal level [23]. Four measurements on the channel are undertaken at each location. In each location, two modes of MIMO operation (conventional MIMO and AB) are measured. The Butler matrices are inserted at both transmitter and receiver when measuring MIMO channels with AB. Figure 7 shows measurement scenarios. We chose measurements in a large room to provide various test conditions. The location of the transmitter is fixed as shown in Figure 7 with rectangular symbol. There are four measured locations for the receiver represented by circular symbol in Figure 7. The antenna is a monopole. The numbers of transmitted and received antennas are 4×4. The center frequency (λ_c) is 2.4 GHz. The normalized separation between transmit and receive antennas (Δ_t, Δ_r) is 0.5. Distance between Tx and Rx locations 1, 2, 3, and 4 is 2.3, 6.1, 6.8, and 13.3 meters, respectively. It is easy to measure both conventional MIMO and AB by using switches presented in Figure 6. The measured results obtained by network analyzer are used as a channel response in MIMO systems. As seen in Figure 6, apart from Butler matrix, all the other components are the same for both conventional MIMO and AB. Therefore, the measured channels can be directly compared to each other as presented in the following. Figure 8 shows the photo of measurement areas for LOS (location 1) and NLOS (location 4).

The channel matrices $\mathbf{H}$ and $\mathbf{H}^b$ can be realized from the measured data from vector network analyzer. The channel fading environments are measured by changing the locations of the receiver. We also believe that the mismatches

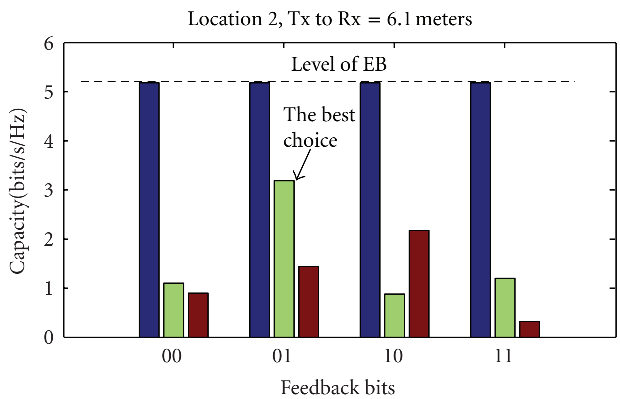


(a) LOS (b) NLOS

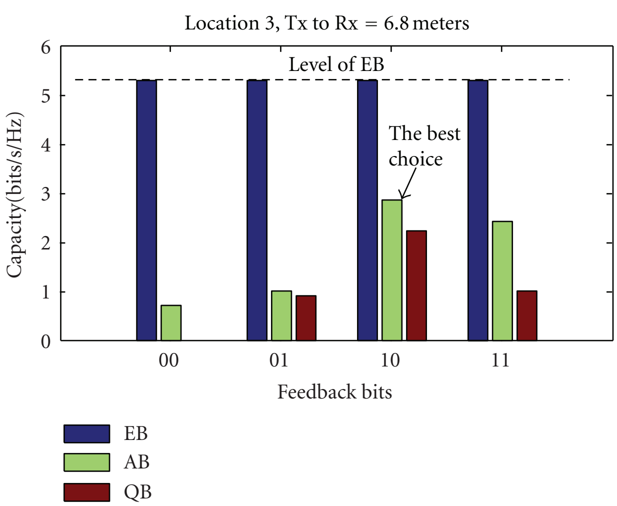
Figure 8: The photo of measurement areas for LOS and NLOS.



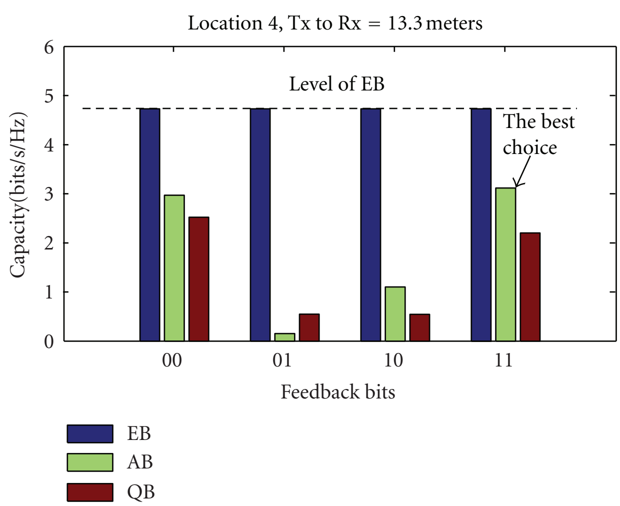
(a)



(b)



(c)



(d)

Figure 9: Average capacity versus beam direction for two-bit feedback, locations 1, 2, 3, and 4.

among RF circuits in transmitting/receiving components and mutual coupling effects are included in the measured channel. We use 2 bits of feedback for QB. The simulations are undertaken by utilizing measured data into MATLAB programming. We have made comparisons between EB, QB, and AB. The capacity results are evaluated by using (12), (15), and (18).

In Figure 9, the average capacity versus beam direction for feedback of two bits is presented, in order to justify the results of all locations at SNR = 10 dB. The results indicate that AB offers a better performance than QB. It is obviously noticed that the benefit of using AB is pronounced at all locations. The gap deviation is about 1.83 bits/s/Hz. Please be reminded that the improvement of MIMO capacity comes at a little expense of inserting Butler matrices at both transmitter and receiver but without any extra complexity when compared with EB.

6. Conclusion

This paper presents the performance of MIMO beamforming systems using EB, QB, and AB techniques. The result reveals that the proposed system, AB technique, is attractive to be practically implemented because it offers a low complexity while offering the similar performance as that of QB. We have also presented the performance of MIMO systems using AB realized by using Butler matrix. Further, the benefit of using AB technique for 4×4 MIMO systems is verified by measured results. The AB method as realized by Butler matrix has been implemented and compared with EB and QB. The results have revealed that the EB outperforms the AB and QB at all locations. The reason for this is that the EB uses the maximum eigenvalue for finding channel capacity. It is concluded that the proposed system is very attractive to practically implement on MIMO systems due to its low cost and complexity.

Acknowledgments

This work is financially supported by Suranaree University of Technology, Thailand, and the Royal Golden Jubilee Program of Thailand Research Fund, Thailand.

References

[1] B. Mondal and R. W. Heath, "Performance analysis of quantized beamforming MIMO systems," *IEEE Transactions on Signal Processing*, vol. 54, no. 12, pp. 4753–4766, 2006.

[2] A. S. Lek, J. Zheng, O. Eric, and J. Kim, "Subspace beamforming for near-capacity performance," *IEEE Transactions on Signal Processing*, vol. 56, no. 11, pp. 5729–5733, 2006.

[3] X. Zheng, Y. Xie, J. Li, and P. Stoica, "MIMO transmit beamforming under uniform elemental power constraint," *IEEE Transactions on Signal Processing*, vol. 55, no. 11, pp. 5395–5406, 2007.

[4] L. Sun, M. R. McKay, and S. Jin, "Analytical performance of MIMO multichannel beamforming in the presence of unequal power Cochannel Interference and Noise," *IEEE Transactions on Signal Processing*, vol. 57, no. 7, pp. 2721–2735, 2009.

[5] S. L. Ariyavisitakul, J. Zheng, E. Ojard, and J. Kim, "Subspace beamforming for near-capacity MIMO performance," *IEEE Transactions on Signal Processing*, vol. 56, no. 11, pp. 5729–5733, 2008.

[6] R. D. Vieira, J. C. B. Brandão, and G. L. Siqueira, "MIMO measured channels: capacity results and analysis of channel parameters," in *Proceedings of the International Telecommunications Symposium (ITS '06)*, pp. 152–157, Fortaleza, Brazil, September 2006.

[7] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311–335, 1998.

[8] I. E. Telatar, "Capacity of multi-antenna Gaussian channels," AT&T Bell Laboratories, Technical Memorandum, 1995.

[9] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell Labs Technical Journal*, vol. 1, no. 2, pp. 41–59, 1996.

[10] J. P. Kermoal, P. E. Mogensen, S. H. Jensen et al., "Experimental investigation of multipath richness for multi-element transmit and receive antenna arrays," in *Proceedings of the 51st Vehicular Technology Conference 'Shaping History Through Mobile Technologies' (VTC '00)*, pp. 2004–2008, May 2000.

[11] R. Stridh, B. Ottersten, and P. Karlsson, "MIMO channel capacity on a measured indoor radio channel at 5.8 GHz," in *Proceedings of the 34th Asilomar Conference*, pp. 733–737, November 2000.

[12] A. F. Molisch, M. Steinbauer, M. Toeltsch, E. Bonek, and R. S. Thomä, "Capacity of MIMO systems based on measured wireless channels," *IEEE Journal on Selected Areas in Communications*, vol. 20, no. 3, pp. 561–569, 2002.

[13] L. Huang, J. W. M. Bergmans, and F. M. J. Willems, "Low-complexity LMMSE-based MIMO-OFDM channel estimation via angle-domain processing," *IEEE Transactions on Signal Processing*, vol. 55, no. 12, pp. 5668–5680, 2007.

[14] L. Huang, C. K. Ho, J. W. M. Bergmans, and F. M. J. Willems, "Pilot-aided angle-domain channel estimation techniques for MIMO-OFDM systems," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 2, pp. 906–920, 2008.

[15] A. F. Molisch, X. Zhang, S. Y. Kung, and J. Zhang, "DFT-based hybrid antenna selection schemes for spatially correlated MIMO channels," in *Proceedings of the 14th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC '03)*, pp. 1119–1123, September 2003.

[16] A. Innok, M. Uthansakul, and P. Uthansakul, "The enhancement of MIMO capacity using angle domain processing based on measured channels," in *Proceedings of the Asia Pacific Microwave Conference (APMC '09)*, pp. 2172–2175, Singapore, December 2009.

[17] A. Grau, J. Romeu, S. Blanch, L. Jofre, and F. De Flaviis, "Optimization of linear multielement antennas for selection combining by means of a butler matrix in different MIMO environment," *IEEE Transactions on Antennas and Propagation*, no. 11, pp. 3251–3264, 2006.

[18] P. Uthansakul, A. Innok, and M. Uthansakul, "Open-loop beamforming technique for MIMO system and its practical realization," *International Journal of Antennas and Propagation*, vol. 1, 13 pages, 2011.

[19] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*, chapter 7, Cambridge, UK, 2005.

[20] R. G. Tsoulos, *MIMO Systems Technology for Wireless Communications*, The Electrical Engineering and Applied Signal Processing Series, chapter 4, 2006.

[21] P. Uthansakul, *Adaptive MIMO Systems Explorations For Indoor Wireless Communications, Appendix D*, 2009.

[22] J. C. Liberti and J. T. S. Rappaport, *Smart Antennas for Wireless Communications*, IS-95 and Third Generation CDMA Applications, chapter 3.

[23] N. Promsuvana and P. Uthansakul, "Feasibility of adaptive 4 × 4 MIMO system using channel reciprocity in FDD mode," in *Proceedings of the 14th Asia-Pacific Conference on Communications (APCC '08)*, pp. 1–5, October 2008.