

Feasibility of Adaptive 4x4 MIMO System using Channel Reciprocity in FDD mode

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Abstract- The knowledge of state information (CSI) is necessary to be known at transmitter in a Multiple Input Multiple Output (MIMO) system in order to improve the capacity performance. Among methods to realize CSI at transmitter, the use of reciprocity principle is the most attractive technique for implementation. This is because CSI at transmitter is easily estimated by the reverse channel where the forward and reverse channels are symmetrically considered in time, frequency and location. In Frequency Division Duplex (FDD) mode, forward and reverse links are allocated by different frequency thus channel reciprocity fails under this condition. In this paper, the capacity performances of adaptive 4x4 MIMO system based on measured data are presented. Also the feasible method to compensate the differences between TDD and FDD channels is studied. The results reveal that the capacity of adaptive MIMO system in FDD mode can be improved by compensation technique.

Keywords: MIMO; FDD; Performance; Compensation; Measurement

I. INTRODUCTION

A Multiple-Input-Multiple-Output (MIMO) system is the system with antenna arrays at both transmitter and receiver [1]. It proposes an extensive improvement over conventional smart antenna systems in both Quality of Service (QoS) and the transfer rate. The channel capacity of MIMO system can grow linearly as the number of antenna pairs between transmitter and receiver. In addition, several works have shown that the capacity can be further improved if the forward Channel State Information (CSI) is known at the transmitter [2-4]. When forward CSI is known at transmitter, the transmitted signals are able to be adjusted according to the known CSI in order to achieve the maximum capacity. This system is called as the adaptive system and the algorithm to adjust transmitted signal is well-known as Water-Filling (WF) algorithm. However, the transmitter is not able to know forward CSI unless the receiver sends it back via reverse channel. The cost of feedback CSI and huge overhead in transmission make the adaptive system far away from implementation.

In general, the CSI is not usually available at the transmitter. From literatures, there are two approaches in order for the transmitter to obtain the CSI. The first approach utilizes CSI from feedback channel and the second approach is based on the reciprocity principle. In the first method, the forward channel is estimated at receiver and then it is sent back to the transmitter through the reverse channel. This method does not function properly if the channel is rapidly changed. In order to realize the correct CSI at transmitter, more frequent

estimations and feedbacks are needed. As a result, the overheads for the reverse channel become prohibitive. In turn, the second approach based on reciprocity does not have such a problem. Due to the reciprocity principle, it is well known that the radio propagation channel is reciprocal between two antennas. Ideally, the forward and reverse channels are assumed to be the same. Therefore, the transmitter can realize the forward CSI by estimating the reverse CSI instead. This assumption can be acceptable for system operating in Time Division Duplex (TDD) mode because both forward and reverse channels are on the same frequency. In Frequency Division Duplex (FDD) mode, the forward and reverse channels are allocated by different carrier frequency at the same time. Therefore, it is obvious that the reciprocity approach fails on FDD mode which transmitter is not able to directly realize CSI from reverse channel.

Most works in the area of channel reciprocity for MIMO system [5-6] are based on TDD mode by assuming the reciprocity between forward and reverse channels. Although there are many factors in TDD mode such as interferences along with transmission and imperfection of Radio Frequency (RF) components, which cause the deficient reciprocity. But it has been ignored and accepted for practical use. So far in literatures, there has not been any research which concerns the problem in FDD mode. Because there are many tradeoffs between TDD and FDD mode, it is interesting to realize the performance of reciprocity approach when applying in FDD mode instead of TDD mode. In this paper, the performances of adaptive MIMO system based on channel reciprocity in FDD mode are investigated. The deviation of forward and reverse channels is examined to justify the use of reciprocity by measured data and the way to compensate the deviation of forward and reverse channel is also investigated in order to improve capacity of system. The 4x4 MIMO channels are measured and then the channel capacity is calculated by simulations. In addition, the comparison between feedback approach and reciprocity approach are also undertaken to provide the fair judgment with measured data. The results in this paper are helpful to realize the feasibility of channel reciprocity for MIMO system in FDD mode.

The remainder of this paper is organized as follows. In Section II, the system model and the concept of channel estimation are presented. Section III, the channel measurement is described. The simulation results are presented in Section IV. Finally, the paper conclusion is given in Section V.

II. SYSTEM MODEL

A. MIMO system model

Considering the MIMO system which has N_T transmit antennas and N_R receive antennas, the formula of MIMO channel capacity is given in (1) [7]. This expression presents the averaging capacity in bps/Hz by assuming the ergodic process for channel matrix \mathbf{H} .

$$C = E_H \left\{ \log_2 \det \left(\mathbf{I}_{N_R} + \frac{P_T}{P_N N_T} \mathbf{H} \mathbf{H}^* \right) \right\} \quad (1)$$

Where \mathbf{I}_N is the $N_R \times N_R$ identity matrix, P_T is the total transmit power, P_N is the noise power, N_T is the number of transmit antennas, N_R is the number of receive antennas, $E_H\{ \}$ is the expectation over \mathbf{H} and $*$ denotes the conjugate and transpose operation.

The channel matrix \mathbf{H} is performed by Singular Value Decomposition (SVD) technique given in (2)

$$\mathbf{H} = \mathbf{U} \mathbf{D} \mathbf{V}^* \quad (2)$$

Where the matrices \mathbf{U} , \mathbf{V} are unitary of dimensions $N_R \times N_R$ and $N_T \times N_T$ accordingly, while \mathbf{D} is non-negative and diagonal with diagonal elements $\sqrt{\lambda_i}, i = 1, \dots, l$, are the singular values of matrix \mathbf{H} and $l = \text{rank}(\mathbf{H}) \leq \min(N_R, N_T)$ is the rank of \mathbf{H} . Then (1) can be expressed as

$$C = \sum_{k=1}^n \log_2 \left(1 + \frac{P_T}{N_T} \lambda_k \right) \quad (3)$$

Where $n = \min(N_R, N_T)$. Hence, the MIMO channel is equivalent to L independent Single-Input-Single-Output (SISO) sub channels in parallel.

For adaptive MIMO system, it is well known that the WF algorithm [9] can be used to optimally allocate the transmitted power. It improves the sum capacity when perfect CSI is available at the transmitter. By using WF, (3) can be expressed as

$$C = \sum_{k=1}^n \log_2 (1 + P_k \lambda_k) \quad (4)$$

$$P_k = (\mu + \lambda_k^{-1})^+ \quad (5)$$

Where μ is chosen to satisfy

$$\sum_{k=1}^n P_k = P_T \quad (6)$$

P_k is the power that is assigned to the k th sub channel and λ_k are the eigenvalue of $\mathbf{H} \mathbf{H}^\dagger$.

B. Least Squares Channel Estimation

The success of adaptive system depends on how perfect CSI estimated at transmitter and receiver. However, in a practical system, the realization of perfect CSI is not

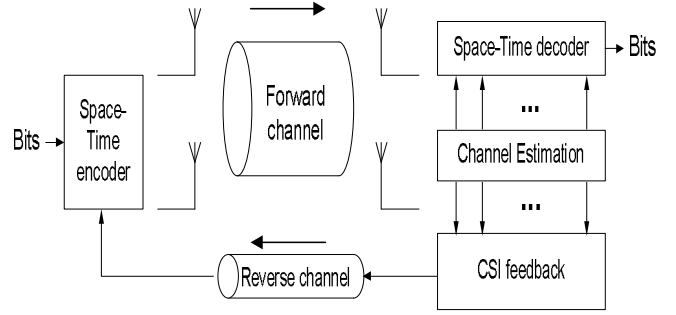


Figure 1. MIMO model with feedback channel

possible. The quality of CSI achieved at transmitter and receiver relies on the efficiency of estimation algorithm. In practice, there are a lot of methods to perform channel estimation. Among those methods, the training sequence is the simplest and lowest complexity. Least squares (LS) channel estimation [8] is one kind of training sequence which the paper adopts this method for simulations.

Considering N_T transmit antennas and N_R receive antennas, the training sequence of n th transmit antenna is represented as

$$\mathbf{x}_n = [x_n(0) \quad x_n(1) \quad \dots \quad x_n(L-1)]$$

Where $n=1, 2, 3, \dots, N_T$ and $L (> N_T)$ is the length of the training sequence. Because the symbols are transmitted from N_T transmit antennas in parallel, the $N_T \times L$ training sequence matrix is generated as follows

$$\mathbf{x} = [x_1 \quad x_2 \quad \dots \quad x_{N_T}]$$

The overall received signals can be represented as

$$\mathbf{y} = \mathbf{H} \mathbf{x} + \mathbf{n} \quad (7)$$

Where \mathbf{y} and \mathbf{n} are $N_R \times L$ matrix of received signals and noises, respectively. The channel matrix \mathbf{H} is estimated by help of training sequences. It is obvious that the maximum likelihood estimation of the channel matrix is given by

$$\hat{\mathbf{H}} = \mathbf{y} \mathbf{x}^\dagger \quad (8)$$

Where $(\)^\dagger$ means pseudo-inverse and by substitute (7) in (8) thus the channel estimation error matrix can be denoted as

$$\boldsymbol{\varepsilon}_E = \mathbf{n} \mathbf{x}^\dagger \quad (9)$$

C. Channel State Information(CSI) at transmitter

As seen in Section A, the system achieves the optimal capacity when the transmitter has knowledge of the forward channel. To obtain the CSI at transmitter, there are two approaches explained as follows.

1) *Feedback approach*

For this approach, the receiver realizes a current CSI by LS channel estimation and then feeds it back to the transmitter through reverse channel. The configuration of feedback approach is shown in Figure 1.

In Figure 1, the receiver uses the estimated channel to extract the data and to generate the feedback CSI. The feedback CSI is sent back to the transmitter using the feedback control channel. It is assumed that channel state information is perfectly known at the transmitter. The transmitter, in turn, uses this information to customize the transmitted signal for the channel.

In a practical system, errors from feedback link which influences to channel knowledge cannot be neglected. This effect can degrade the capacity performance and it is more pronounced when feedback link contain errors excessively, under this assumption the available CSI at transmitter can be expressed as

$$\mathbf{H}_T = \mathbf{H} + \boldsymbol{\varepsilon}_E + \boldsymbol{\varepsilon}_F \quad (10)$$

Or

$$\mathbf{H}_T = \hat{\mathbf{H}} + \boldsymbol{\varepsilon}_F \quad (11)$$

Where \mathbf{H} is the forward channel and $\boldsymbol{\varepsilon}_F$ is the $N_R \times N_T$ error matrix from feedback link assumed as complex Gaussian distribution with zero mean and variance σ_F^2 .

2) *Reciprocity Approach*

According to principle of reciprocity, the forward and reverse channels are identical when time, frequency and antenna locations are the same. Based on the principle, the transmitter may use the CSI obtained by the reverse link for the forward link. In practice, the forward and reverse channels are not truly identical to each other because the effect of channel fadings, noises and environments. It is ignored in literatures for TDD mode but it is not applicable for FDD mode.

Considering MIMO system with LS channel estimation, the CSI known at transmitter can be given by

$$\mathbf{H}_T = \mathbf{H} + \boldsymbol{\varepsilon}_E + \boldsymbol{\varepsilon}_R \quad (12)$$

Or

$$\mathbf{H}_T = \hat{\mathbf{H}} + \boldsymbol{\varepsilon}_R \quad (13)$$

Where $\boldsymbol{\varepsilon}_R$ is the $N_R \times N_T$ channel reciprocity error matrix realized by the measurement.

D. *Property of forward and reverse channels in FDD mode*

Following the propagation model described in [9-10], the channel response is consisted of multipath signals. The channel response of forward link can be modeled as

$$h = \sum_{i=1}^n \frac{\lambda}{(4\pi d_i)} e^{j\phi_i} \quad (14)$$

Where

$$\phi_i = \frac{2\pi d_i}{\lambda}$$

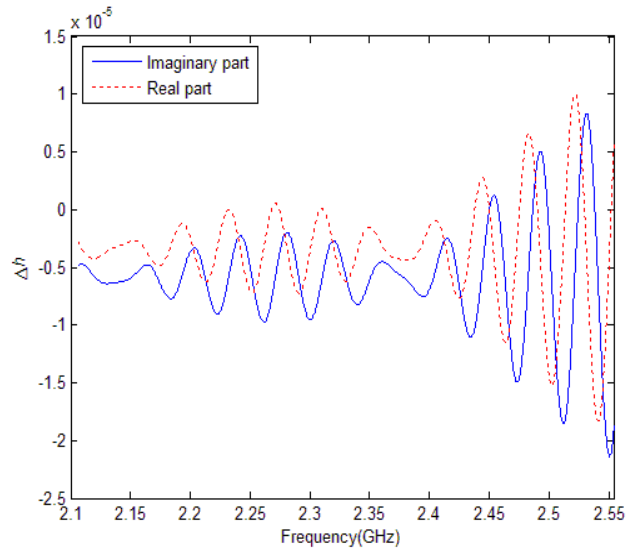


Figure 2. Real and imaginary part of Δh versus operating frequency

Where ϕ_i and d_i are the phase and distance of the i th multipath.

In FDD mode, forward and reverse links are different in frequency but both frequencies should be allocated in the adjacent frequency band due to the limitation of RF hardware. Therefore, it makes sense to assume that reverse channel experiences the same multipath as forward channel. Then channel response of reverse link in FDD mode is modeled as

$$h_r = \sum_{i=1}^n \frac{(\lambda + \Delta\lambda)}{(4\pi d_i)} e^{j\phi_{r_i}} \quad (15)$$

Where

$$\phi_{r_i} = \frac{2\pi d_i}{\lambda + \Delta\lambda}$$

Where ϕ_{r_i} is the phase of the i th multipath in reverse direction.

The difference between forward and reverse channel can be formed in term of real and imaginary parts as shown in (16)

$$\Delta h = \left[\sum_{i=1}^n \frac{\lambda}{(4\pi d_i)} \cos \phi_i - \frac{(\lambda + \Delta\lambda)}{(4\pi d_i)} \cos \phi_{r_i} \right] + j \left[\sum_{i=1}^n \frac{\lambda}{(4\pi d_i)} \sin \phi_i - \frac{(\lambda + \Delta\lambda)}{(4\pi d_i)} \sin \phi_{r_i} \right] \quad (16)$$

Because $\Delta\lambda$ is very little due to the nearby frequencies between forward and reverse links, then (16) can be reduced to

$$\Delta h = \frac{\lambda}{(4\pi)} \left[\left(\sum_{i=1}^n \frac{1}{d_i} (\cos \phi_i - \cos \phi_{r_i}) \right) + j \left(\sum_{i=1}^n \frac{1}{d_i} (\sin \phi_i - \sin \phi_{r_i}) \right) \right] \quad (17)$$

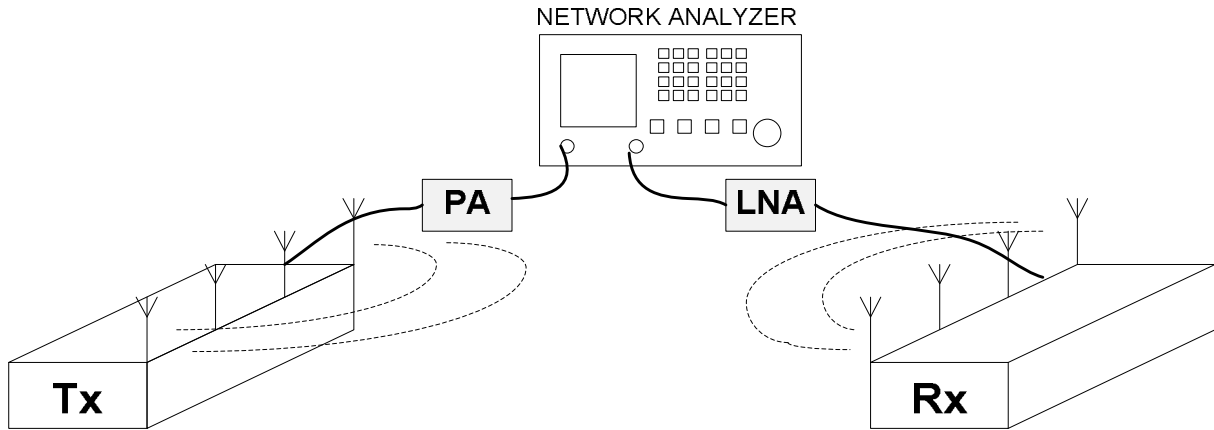


Figure 3. Measurement set up

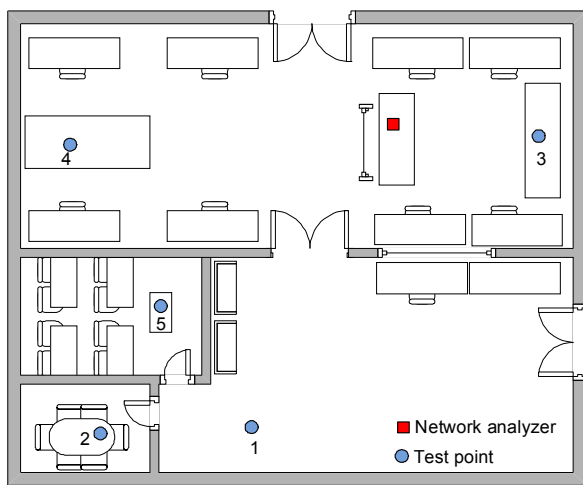


Figure 4. Map of measured area

In Figure 2, it shows the difference between forward and reverse channels using (17) where the carrier frequency of forward link is 2.45GHz and then the carrier frequency of reverse link span from 2.1 to 2.55 GHz. It is assumed that there are 10 multipath signals. As seen in Figure 2, Δh which is lower than 2.45GHz swings over a constant value. It means that this constant value can be used as the representative of a whole frequency band to approximately adjust reverse channel to be forward channel in FDD mode.

III. MEASUREMENT

The configuration of measurement setup for 4x4 MIMO system is shown in Figure 3.

As seen in Figure3, the Power Amplifier (PA) is used at transmitter to provide more transmitted power. In turn, Low Noise Amplifier (LNA) is used to increase the received signal level. The channel coefficients in both magnitude and phase are directly measured by network analyzer. To provide the reliability of measured data, the channel measurements are undertaken by five times in the different days.

For the measured area, we choose the large office room to provide many scenarios of study. Figure 4 shows the map of office room. The circular markers are referred to

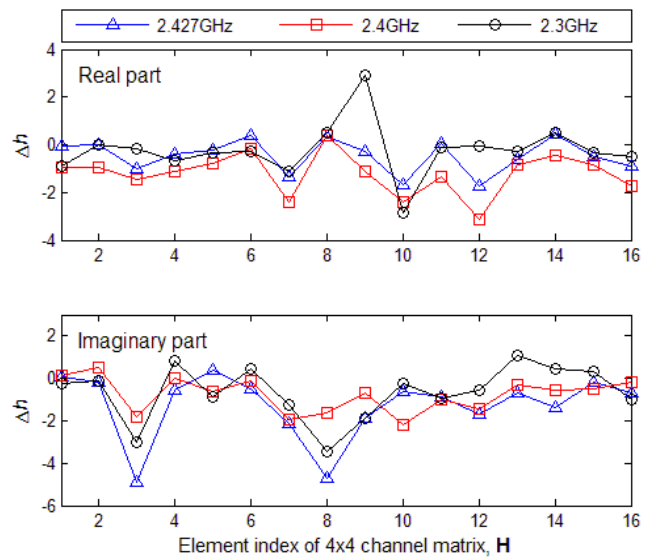


Figure 5. Measured data of Δh at location 4

the locations where the measurement is undertaken. There are five measured locations. In each location transmitter and receiver are switched in order to measure the forward and reverse channel. Although, it is easier to measure both forward and reverse channels by switching transmitted port in network analyzer but the effect of non similarity of PA and LNA including feeding cables might differ the measured channel from the real results. Therefore, we choose to switch all parts of transmitter and receiver in order to avoid any false outcomes. The measured results achieved by switching are both forward and reverse channels so these channels are directly used as a channel response in the following simulations.

IV. RESULTS AND DISCUSSIONS

The simulations are undertaken by MATLAB programming and the capacity results are evaluated by using (4). For the feedback approach, the assumptions in (9), (10) are used. The authors also assumed that, the mismatches among RF circuits in transmit/receive components and mutual coupling effects are ignored and the channel matrix \mathbf{H} are normalized to provide a comparable discussion by $\sum |\mathbf{H}_{ij}|^2 = N_T N_R$.

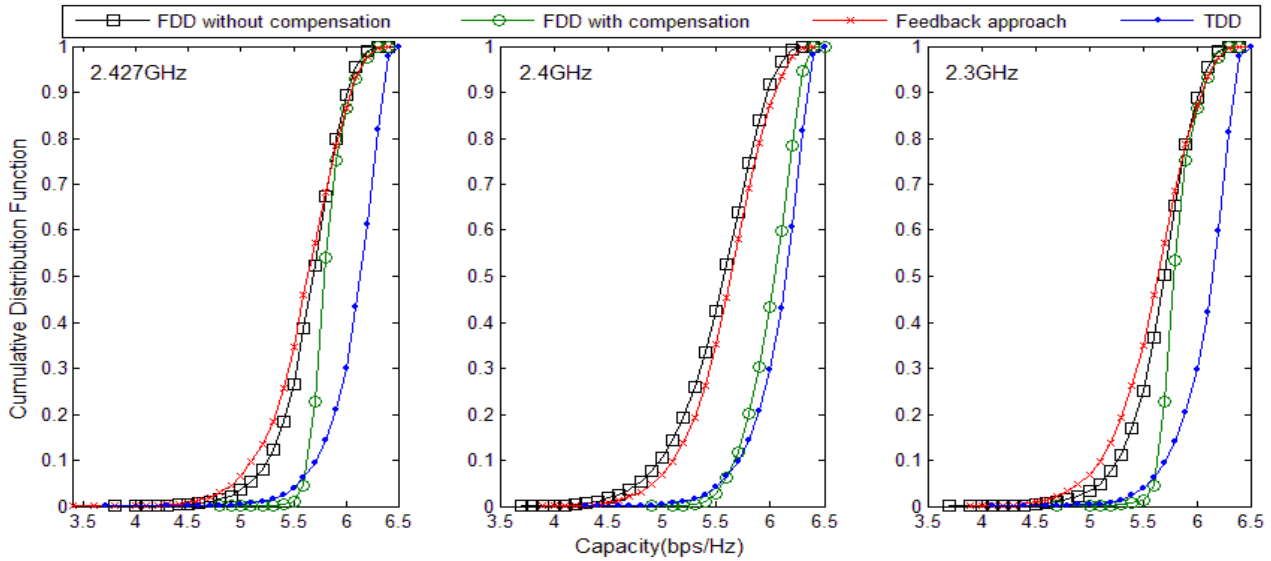


Figure 6. Cumulative distribution function of capacity comparison on different carrier frequency at location 4

Figure 5 shows the measured data of Δh at location 4 for forward link at 2.45 GHz and reverse link at 2.427, 2.4, 2.3 GHz. As seen in Figure 5, the patterns of three curves are similar and their values are close to each other for both real and imaginary parts. This result confirms the conclusion which is made on Figure 2. For other locations, the trend of three curves is as considerably same as shown in Figure 5. Therefore, this paper uses the average value of all three curves to be the specific values for compensating the reverse channel.

Figure 6 shows the Cumulative Distribution Function (CDF) of capacity for forward link at 2.45 GHz and reverse link at 2.427, 2.3, 2.4 GHz. Both feedback and reciprocity approaches are undertaken. For reciprocity approach, the use of reverse channel as forward channel is applied to both TDD and FDD modes. For FDD mode, the compensation using average values presented in Figure 5 is also simulated. As seen in Figure 6, the FDD with compensation offers better performance than FDD without compensation and feedback approach. This compensation technique can improve capacity about 15% at 2.4 GHz.

V. CONCLUSIONS

This paper presents the performance of adaptive MIMO system using CSI from reverse FDD channel. Also the compensation technique based on measured data in FDD mode is introduced. The results reveal that the compensation can improve capacity for every location. This feasibility study is a guideline to improve the performance of MIMO system for FDD transmission in practice.

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