Measurement-Based Multiplexing Mode Selection for Codebook-Based MIMO Systems

Junjun Gao, Jianhua Zhang and Xiaofeng Tao
Key Laboratory of Universal Wireless Communications, Ministry of Education,
Beijing University of Posts and Telecommunications (BUPT), China
Email: {gaojunjun, jhzhang, taoxf}@bupt.edu.cn

Abstract—**Based on the channel measurement in a typical indoor environment, a simple mode selection criterion is originally proposed for closed-loop multiplexing transmissions using LTE codebook. The fitting result of the capacity loss (CL) due to the limited size codebook is presented. High signal-to-noise ratio (SNR) analysis is also given to provide a deep insight for the addressed mode selection problem. Furthermore, the effect of the codebook design and dimension on the capacity loss is also investigated. Though based on a specific environment, the generality of the proposed algorithm is validated using ITU-R M.2135 channel model in four scenarios. The results are important for the adaptive technique development in modern communication systems.**

I. Introduction

Multiple-input multiple-output (MIMO) techniques have attracted lots of research recently [1]. The selection of different MIMO transmission modes is very important to meet the link robust and spectral efficiency requirement in practice. The switching between the transmit diversity (TD), beamforming (BF) and open-loop spatial multiplexing (SM) schemes is studied in [2], [3] to maximize the channel ergodic capacity. Precoding can be performed to achieve different rank SM transmissions if the channel state information (CSI) is available at the transmitter. The indoor channel is usually slow time-varying as a result of the low mobility terminals, which is beneficial to apply closed-loop technique to acquire the CSI. The rapid data traffic growth in indoor scenarios brings a great challenge to the spectral efficiency in modern communication systems. It is shown in [4] that considerable average capacity is achieved in indoor line-of-sight (LOS) scenario. Due to the rich scatterers [5] and short access distance in indoor environments, the switching between different rank closed-loop SM transmissions is important to satisfy the high spectrum efficiency requirement in practice.

However, it is unrealistic to send the perfect CSI back to the transmitter. Standardized in LTE by 3GPP, a common codebook table is shared between the transmitter and receiver, only the rank indicator (RI) and precoding matrix indicator (PMI) are fed back to indicate the SM mode and corresponding precoding matrix (PM) [6]. Traditional minimum mean square error post (MMSE-Post) based and mutual information (MI) based RI selection criterions are discussed in [7], [8]. The disadvantage of these criterions is the high complexity caused by many matrix inversions to calculate the signal-to-interference-noise ratio (SINR). However, to the best of our knowledge, simple SM mode (RI) selection criterion from channel perspective is not available for codebook-based MIMO system in current literatures.

Based on the channel measurement in a typical indoor environment, a simple SM mode selection criterion is proposed for 4×2 closed-loop MIMO system using LTE codebook. Hence, the switching between different SM modes is only dependent on the operating SNR and minimum channel eigenvalue. The results prove that the average capacity loss (CL) for full-rank SM transmission can be expressed as a power function of the minimum channel eigenvalue. High SNR analysis is presented to provide deep insight for the SM mode selection problem. The effect of the codebook design and dimension on the CL is also investigated. Though based on a specific environment, the generality of the proposed algorithm is validated using ITU-R M.2135 channel model in four scenarios [9], [10]. The simulations show that the proposed criterion is nearly capacity lossless. The proposed method can be generalized for other practical MIMO configurations (e.g. 8×2 and 4×4) and new codebook design to reduce the complexity of the adaptive algorithms.

The rest of this paper is organized as follows. Section II describes the measurement environment. Section III introduces the system model. Measurement-based mode selection is proposed in Section IV. Section V presents the simulations. Finally, a summary of this letter is given in Section VI.

II. Measurement Description

A. Measurement System

Measurement was performed in a teaching building of Beijing University of Posts and Telecommunications utilizing the Elektrobit PropSound Channel Sounder system illustrated in Fig. 1. External RF conversion modules are deployed at both transmit and receive sides to support the operating frequency. Uniform linear array (ULA) with four dipoles has been equipped at both sides, which can be replaced by omni-directional array (ODA) to extract spatial angle parameters of multipaths. One complete set of MIMO channel realization called cycle is captured in a time-division multiplexing (TDM) method. The measurement of each antenna pairs is accomplished with the help of the high speed antenna switching unit (ASU) to transfer the antennas in sequence. Before the measurement, a back-to-back test is required to obtain the system response for calibration purpose, where the transmitter

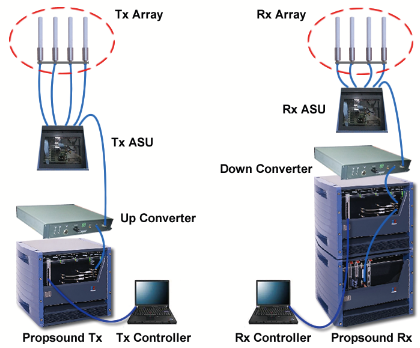

Fig. 1. The setup of the MIMO channel measurement system.

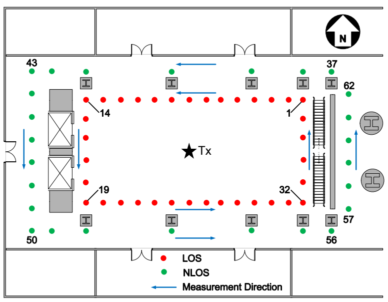

Fig. 2. Measurement layout and measurement position map in different propagation conditions.

and receiver are connected directly by cable using a 50 dB attenuator to prevent power overload at the receiver.

B. Measurement Environment

The measurement was performed in a typical indoor hall of Beijing University of Posts and Telecommunications. The layout and measurement position arrangement are shown in Fig. 2, where the measurement position index and moving direction are marked out. The red and green colors represent LOS and NLOS propagations respectively. The height of the Tx array marked by black pentacle is 3 m. The Tx array remained stationary in the center of the hall during the experiment. The channel is sampled in a fixed-position method. The receiver moved to the next measurement position if more than 700 sets of channel realizations are collected. The separation between two adjacent LOS measurement positions is 1.6 m (32 wavelengths). Several NLOS measurement positions behind the square columns (1.2m×1.2m), concrete walls and evaluators are deliberately planned for comparison. Total number of LOS and NLOS measurement positions are 36 and 26 respectively. Reflected and scattered components are created by the surrounding walls, columns, evaluators, stairs and people. The detailed measurement configuration is listed in Table I.

III. System Model

Considering a MIMO system with N_t transmit and N_r receive antennas, the channel matrix is denoted as $\mathbf{H} \in \mathcal{C}^{N_r \times N_t}$.

TABLE I
MEASUREMENT CONFIGURATION

Items	Settings
Center Frequency (GHz)	6
Bandwidth (MHz)	100
PN Code Length (chips)	255
Type of Antenna	ULA
Number of Transmit antenna	4
Number of Receive antenna	4
Element Space of Tx (λ)	1
Element Space of Rx (λ)	0.5
Height of Tx Antenna (m)	3
Height of Rx Antenna (m)	1.8

Assuming $N_t \geq N_r$, the received signal can be represented as

$$\mathbf{y} = \mathbf{HPs} + \mathbf{n}. \tag{1}$$

where $\mathbf{y} \in \mathcal{C}^{N_r \times 1}$ is the received vector, and $\mathbf{n} \in \mathcal{C}^{N_r \times 1}$ is the additive noise vector. The effective $L \times 1$ transmit symbol vector is $\mathbf{s} = [s_1, \cdots, s_L]^{\mathrm{T}}$, and L is the SM rank. $\mathbf{P} \in \mathcal{C}^{N_t \times L}$ is the unitary precoding matrix satisfying $\mathbf{P}^{\dagger}\mathbf{P} = \mathbf{I}_L$.

Linear receiver can be used to recover the symbol of each stream with low complexity, and we consider minimum mean square error (MMSE) receiver in this paper. Assuming uniform power allocation, the SINR of the l-th stream is [11], [12]

$$SINR_l = \frac{1}{\left\{\left(\mathbf{I} + \frac{\gamma_0}{L}\mathbf{P}^{\dagger}\mathbf{H}^{\dagger}\mathbf{HP}\right)^{-1}\right\}_{l,l}} - 1. \tag{2}$$

Given the precoding matrix $\mathbf{P}$, the total capacity of the rank-L transmission with MMSE receiver can be represented as

$$C_L\left(\mathbf{P}\right) = \sum_{l=1}^{L} \log_2\left(1 + SINR_l\right). \tag{3}$$

The SVD of $\mathbf{H}^{\dagger}\mathbf{H}$ is $\mathbf{V}\mathbf{\Lambda}\mathbf{V}^{\dagger}$, where the matrix $\mathbf{V}$ is unitary. The ordered nonzero diagonal elements of $\mathbf{\Lambda}$ are $\lambda_{\max} = \lambda_1 \geq \cdots \geq \lambda_{N_r} = \lambda_{\min} > 0$, and λ_l is the l-th eigenvalue of $\mathbf{H}^{\dagger}\mathbf{H}$. For rank-$L$ transmission, the perfect precoding matrix $\mathbf{P} = \mathbf{V}_L$ is the first L columns of $\mathbf{V}$, $\mathbf{V}_L = [\mathbf{v}_1, \cdots, \mathbf{v}_L]$, where $\mathbf{v}_k$ denotes the k-th column of $\mathbf{V}$.

With limited feedback, the perfect CSI is not available in practice. Hence, only the RI and PMI are fed back to the transmitter, which indicate the selected rank and PM based on a common shared table [6]. The optimal rank L_{opt} and precoding matrix $\mathbf{P}_{opt}$ are selected to maximize the capacity

$$\left(L_{opt}, \mathbf{P}_{opt}\right) = \arg \max_{L;\mathbf{P}\in\mathbf{W}_L} \left\{C_L\left(\mathbf{P}\right)\right\} \tag{4}$$

where $\mathbf{W}_L$ is the codebook for rank-L SM transmission.

IV. Measurement-based Mode Selection

A. Measurement-based RI Selection Criterion

Based on the measured channel data, we evaluated the performance of the 4×2 closed-loop SM transmission using LTE codebook. Then all the channel characteristic sets $(\log_{10}\gamma_0, \lambda_2)$ are divided into two groups, where L1 and L2 transmissions are optimum respectively. The notations L1 and L2 represent rank-1 and rank-2 SM transmissions respectively.

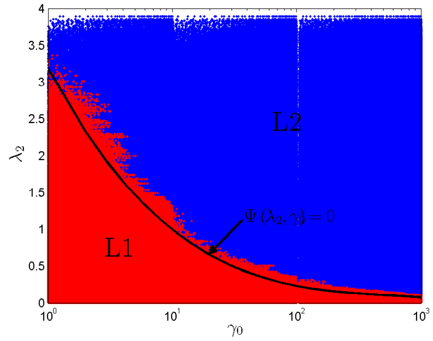

Fig. 3. Illustration of RI decision area between L1 and L2 SM transmissions.

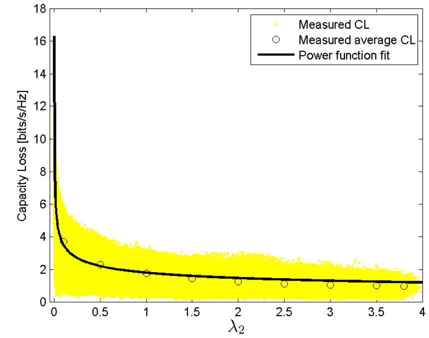

Fig. 4. The measured CL and the power function fit for L2 transmission using LTE codebook with MMSE receiver.

Considering the large SNR dynamic range, the logarithmic operation is to simplify the data processing as much as possible. With the grouped channel characteristic data, the key step is finding simple and proper functions to complete the SM mode switching at the cost of lowest performance degradation. The polynomial function is found to be a good candidate to solve the SM mode selection problem, which can be easily realized in practical hardware platform (e.g. DSP). Details of the parameters fitting process are omitted due to the limited space. To introduce the proposed SM mode selection criterion, we first define a function as follows

$$\begin{aligned}\Psi\left(\lambda_2,\gamma_0\right)=&\lambda_2+0.1356(\log_{10}\gamma_0)^3\\&-1.117(\log_{10}\gamma_0)^2+3.167\log_{10}\gamma_0-3.184\end{aligned} \tag{5}$$

Then the RI selection criterion is expressed as

$$L_{opt}=\begin{cases}1, & \Psi\left(\lambda_2,\gamma_0\right)\le 0\\ 2, & \Psi\left(\lambda_2,\gamma_0\right)>0\end{cases} \tag{6}$$

Note that the channel matrix is power normalized, and satisfying $tr\left(\mathbf{H}^\dagger\mathbf{H}\right)=\sum_{l=1}^{2}\lambda_l=8$. The illustration of the RI decision area is given in Fig. 3. The total sample number of (λ_2,γ_0) is over 10^7 for statistics. The sign of the function $\Psi\left(\lambda_2,\gamma_0\right)$ helps to complete the switching decision between L1 and L2 SM transmissions.

B. High SNR Analysis

The limited size codebook will cause CL [11], which is defined as the capacity gap between the capacity in (3) with perfect PM, $\mathbf{P}=\mathbf{V}_L$, and the capacity with quantized PM. In the high SNR region, the CL is mainly determined by the channel eigenvalues dispersion. The exact CL expressions for single-rank and full-rank SM transmissions are given in our latest literature [12], and the results can be used for the high SNR analysis of the SM mode selection problem. For 4×2 antenna configuration, the CL for L1 and L2 transmissions are respectively

$$C_{loss,1}=-\log_2\sum_{k=1}^{2}\frac{\lambda_k}{\lambda_1}\left|\mathbf{p}_1^\dagger\mathbf{v}_k\right|^2 \tag{7}$$

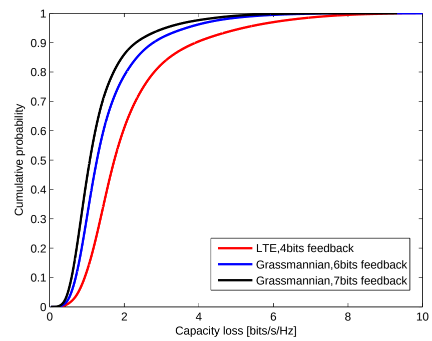

Fig. 5. The effect of codebook dimension on the capacity loss CDF for L2 transmission with MMSE receiver.

$$C_{loss,2}=\sum_{l=1}^{2}\log_2\sum_{k=1}^{2}\frac{\lambda_l}{\lambda_k}\left|\mathbf{p}_l^\dagger\mathbf{v}_k\right|^2 \tag{8}$$

It is shown that L1 transmission suffers very slight CL over the whole SNR region [12]. The limited size codebook only cause a little beamforming direction bias, and leads to a slight SNR decrease compared to the perfect precoding vector. Hence, the CL for L1 transmission can be neglected in the high SNR region.

From (8), it is supposed that the average CL for L2 transmission can be fitted as a function of the minimum eigenvalue under the channel power normalization assumption. Based on the measured channel data, it is found that the power function can provide a good fit for the average CL of the optimum PM, and given by

$$\hat{C}_{loss,2}\left(\lambda_2\right)=1.808\lambda_2^{-0.2892},\qquad \lambda_2\in(0,4] \tag{9}$$

The measured CL and the power function fit for L2 transmission is shown in Fig. 4. The average CL decreases rapidly as the minimum eigenvalue increases. Generally, the capacity loss is influenced by the codebook design and dimension. The capacity loss CDF for the Grassmannian codebook with 6bits and 7bits feedback is plotted in Fig. 5 for comparison. It is shown that increasing the codebook dimension brings limited capacity gain for L2 transmission with MMSE receiver.

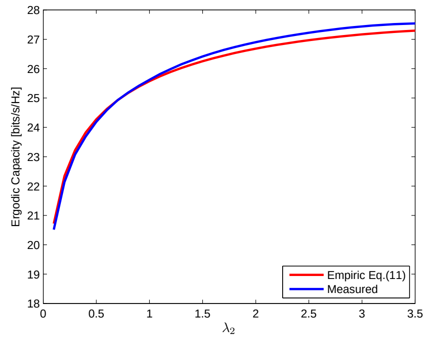

Fig. 6. High SNR validation of the empiric ergodic capacity expression (Eq.(11)) for L2 transmission with MMSE receiver (40dB).

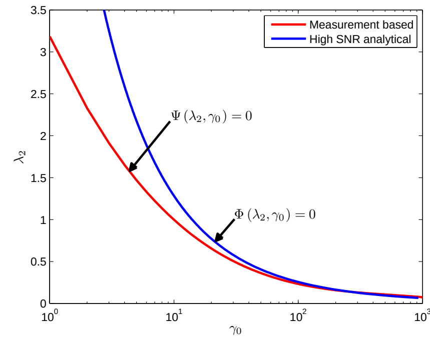

Fig. 7. The measurement-based and high SNR analytical mode switching curves.

With the average CL expression in hand, the ergodic capacity for L1 and L2 transmissions in the high SNR region can approximately represented as

$$C_1 \approx \log_2(\gamma_0 \lambda_1) \tag{10}$$

$$C_2 \approx \sum_{l=1}^{2} \log_2\left(\frac{\gamma_0 \lambda_l}{2}\right) - \hat{C}_{loss,2}(\lambda_2) \tag{11}$$

In the empiric expression (11) for L2 transmission, $\hat{C}_{loss,2}(\lambda_2)$ can be considered as a modified factor caused by the limited size codebook. The validation using measured channel data is given in Fig. 6. The slight capacity deviation for channels with large minimum eigenvalues is caused by the CL fitting process. The channel samples with small minimum eigenvalues ($\lambda_2 < 1$) is much more than that with large minimum eigenvalues ($\lambda_2 > 2$). Hence, the channels with small minimum eigenvalues play a more leading role in the CL fitting (Eq.(11) and Fig. 4), and cause a negligible capacity error for large minimum eigenvalue case.

Substituting (9) into (11) and taking some simple manipulations, the crossing point between the capacity curves for L1 and L2 transmissions will satisfy the following equation

$$\Phi(\lambda_2, \gamma_0) = \gamma_0 \lambda_2 - 2^{1.808\lambda_2^{-0.2892}+2} = 0 \tag{12}$$

The measurement-based switching curve $\Psi(\lambda_2, \gamma_0)$ and high SNR analytical curve $\Phi(\lambda_2, \gamma_0)$ are plotted in Fig. 7. The two curves converge when the SNR is larger than 20dB. It indicates that the proposed criterion is equivalent to maximize the channel ergodic capacity.

C. Adaptive Algorithms

With the measurement-based criterion in hand, the selection of RI only rely on the minimum channel eigenvalue and operating SNR. Hence, the calculation of the RI and PMI can be jointly completed utilizing some current PMI selection criterions. We consider three adaptive algorithms for 4×2 closed-loop SM transmission using LTE codebook, which could achieve a tradeoff between the performance and complexity. The three considered algorithms are described as follows:

1) Traditional algorithm: The optimal SM rank L_{opt} and corresponding PM are chosen from all the possible sets to maximize the capacity by (4). It is the best strategy but at the cost of high calculation complexity. For 4×2 SM codebook of size M, total $2M$ matrix inversions are required to complete the process of the rank and PM selection.

2) Proposed algorithm 1: The optimal SM rank L_{opt} is first calculated using the proposed criterion (Eq.(5) and Eq.(6)). Then the optimal PM is selected from the corresponding codebook set to maximize the capacity according to (2)-(3). Hence, M matrix inversions are needed for each channel matrix.

3) Proposed algorithm 2: The optimal rank is first selected using the proposed RI selection criterion, then the optimal PM is chosen using the minimum subspace angel (MSA) criterion [11] and expressed as (13). This strategy yields the lowest complexity, and no matrix inversion is required.

$$\min_{\mathbf{P} \in \mathbf{W}_L} \left\{ L - \sum_{l=1}^{L} \left| \mathbf{p}_l^{\dagger} \mathbf{v}_l \right|^2 \right\}. \tag{13}$$

V. Validation Results

The proposed SM mode selection criterion is based on a specific environment. We present simulations in this section to validate the generality of the proposed algorithm. Indoor hotspot (InH) and urban microcell (UMi) environments are evaluated using the ITU-R M.2135 channel model [9] at 5.25 GHz. Detail simulation configurations of the four considered scenarios are listed in Table II.

Performance comparisons between three considered adaptive algorithms are given in Fig. 8 and Fig. 9. In LOS cases (Scenario A and Scenario C), three algorithms yield almost the same performance over the whole SNR region. In NLOS cases (Scenario B and Scenario D), the overlap between the capacity curves for traditional algorithm and proposed algorithm 1 indicates that the proposed SM mode selection criterion is nearly capacity lossless. The performance degradation of proposed algorithm 2 relative to proposed algorithm 1 is slight, which is caused by the MSA codebook selection criterion that taking no inter-stream interference into

TABLE II
ITU-R M.2135 SIMULATION CONFIGURATIONS

	A	B	C	D
Scenario Type	InH	InH	UMi	UMi
Propagation Condition	LOS	NLOS	LOS	NLOS
Ms Velocity	1 m/s			
Center Frequency	5.25 GHz			
Tx/Rx Antennas	4 / 2 ULA			
Tx/Rx Antenna Spacing	λ / 0.5 λ		4 λ / 0.5 λ	
Total Drops	10000			

account. The simulations show a fact that the selection of RI and PMI can be independently processed, which is important to simplify the adaptive algorithms. Though based on a specific measurement environment, the results prove the generality of the proposed SM mode selection criterion which can be used in different scenarios and propagation conditions. Moreover, the proposed method can be generalized for other practical MIMO configurations (e.g. 8×2 and 4×4) and codebook design.

VI. CONCLUSION

In this paper, a novel measurement-based multiplexing mode selection criterion is originally proposed for 4×2 closed-loop SM transmission using LTE codebook. The selection of RI is only dependent on the minimum eigenvalue and operating SNR. It is found that the power function can provide a good fit for the measured average CL. High SNR analysis for the SM mode switching problem is given. The generality of the proposed criterion is validated using ITU-R M.2135 channel model in different scenarios and propagation conditions. The simulation results also show that the proposed SM mode selection criterion is nearly capacity lossless. Moreover, the proposed framework can also be generalized for other practical MIMO configuration and codebook design.

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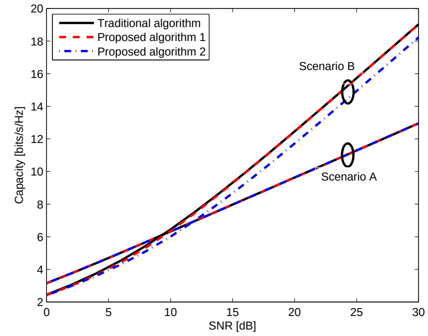

Fig. 8. Performance comparison between considered adaptive algorithms in InH LOS and NLOS scenarios.

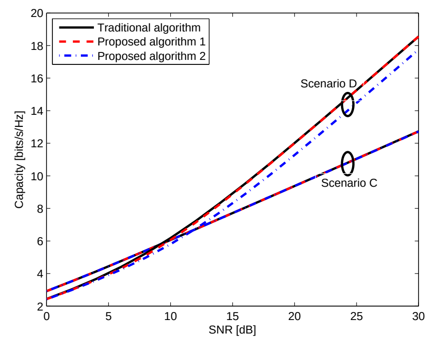

Fig. 9. Performance comparison between considered adaptive algorithms in UMi LOS and NLOS scenarios.

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