Limited Feedback Precoder Design for Spatial Modulation in MIMO Systems

Ming-Chun Lee, Wei-Ho Chung, and Ta-Sung Lee

***Abstract*—We investigate the limited feedback precoding for spatial modulation in multiple-input multiple-output systems via using the codebook. To enhance bit error rate, we propose a codebook design which iteratively trains the codebook by two criteria. The first criterion is to partition the training set by assigning the best codeword to each training symbol; the second criterion is to optimize the codewords according to the assigned training symbols. Simulation results show that the proposed codebook design can effectively improve the SM-MIMO systems with small overhead.**

***Index Terms*—Spatial modulation, MIMO, precoder, codebook, limited feedback.**

I. Introduction

MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) techniques have been widely used in communication systems [1]. However, compared with the baseline single-input single-output (SISO) systems, the disadvantages of conventional MIMO systems are the unfavorable complexity and cost [2], mainly due to the stringent inter-antenna synchronization requirement, the complicated inter-channel interference, and the high cost and energy consumption of the radio frequency (RF) chains [2].

Spatial modulation (SM) in MIMO systems was initially proposed in [3]. The distinction of SM-MIMO is to employ both amplitude and phase modulation (APM) and antenna indices to convey information with only a single activated antenna at each time instant. This enables SM-MIMO to effectively reduce the complexity and cost as well as to improve the energy efficiency (EE) compared with the conventional MIMO [2], [4]. Since SM-MIMO systems have advantages in several aspects compared to conventional MIMO systems, it has recently attracted considerable discussions, including the critical issues and challenges [2], [5].

To enhance the performance of SM-MIMO systems, the adaptive precoder design with the full channel state information at the transmitter (CSIT) can be effective [6], [7]. However, the huge overhead in acquiring full CSIT makes it infeasible in practical systems, especially in frequency division duplex systems. This motivates the investigation of the limited feedback precoding [8]–[11].[1] Although there are literatures related to the limited feedback precoding, we note that [8] was limited in the space shift keying case; [9] utilized only power allocation to improve the systems; [10] used only phase allocation and mainly focused on the MISO channels; [11] provided the diversity analysis over the simple randomly generated codebook to establish the benchmark for the codebook-based precoding. Therefore, by the survey, our goal is to further improve the SM-MIMO systems with limited feedback precoding.

In this paper, we investigate the limited feedback precoder design in SM-MIMO systems employing codebook. By first selecting the codeword, i.e., the precoder, from the codebook according to CSI at the receiver and then feeding back the index to indicate the selected codeword, the precoder can be adaptive with limited feedback. Since the effective codebook is necessary, we propose a codebook design approach in pursuit of the optimal bit error rate (BER) performance via the ideas of Lloyd algorithm [13]. We then provide two criteria to optimize the codebook with a training set. The first criterion is to partition the training set by assigning each training symbol a codeword leading to the minimal BER from a given codebook; the second criterion is to optimize the codewords for BER performance with the aid of the assigned training symbols. By iteratively using these criteria, the codebook can be optimized. Finally, we perform computer simulations to demonstrate the efficacy of the proposed codebook design.

II. Signal and System Model for Precoding-Aided SM-MIMO Systems With Limited Feedback

In this work, we consider the precoding-aided SM-MIMO systems using codebook with N_t transmit antennas and N_r receive antennas. The signal model of the SM-MIMO systems with flat fading channels is given by

$$\mathbf{y} = \sqrt{\rho}\,\mathbf{H}p_{i,k}\mathbf{x}_i + \mathbf{n}, \tag{1}$$

where $\mathbf{y} \in \mathbb{C}^{N_r\times 1}$ is the received symbol, $\mathbf{H} \in \mathbb{C}^{N_r\times N_t}$ is the small-scale fading channel matrix, $\mathbf{x}_i \in \mathbb{C}^{N_t\times 1}$ is the ith transmitted SM symbol, ρ is the average signal-to-noise power ratio (SNR), $p_{i,k} \in \mathbb{C}$ is the precoding weight for $\mathbf{x}_i$ of the kth precoder, and $\mathbf{n} \in \mathbb{C}^{N_r\times 1}$ is the complex white Gaussian noise with unit variance. With the size of APM being M, the SM symbol is further expressed as

$$\mathbf{x}_i = \mathbf{e}_n s_m, \tag{2}$$

where $i = (m-1)N_t + n$; $n = 1, \ldots, N_t$; $m = 1, \ldots, M$; s_m is the mth APM symbol in the adopted APM constellation; $\mathbf{e}_n$ is the nth standard unit vector in which only the nth element is one and the others are zero. Considering the kth precoder (codeword) given by

$$\mathbf{p}_k = \left[p_{1,k}, p_{2,k}, \ldots, p_{N_c,k}\right], \tag{3}$$

[1] The complementary category of limited feedback adaptive design, which adaptively selects the optimal signal-space constellation for transmission, has been discussed in [12].

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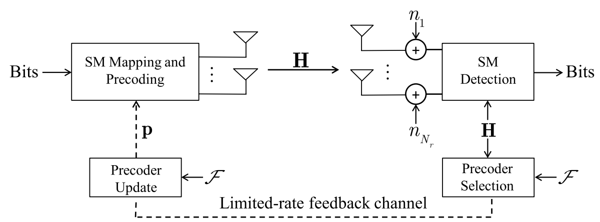

Fig. 1. System model for SM-MIMO with limited feedback precoding.

where $N_c = MN_t$, the codebook with size $Q = 2^B$ known at both the transmitter and receiver is given by $\mathcal{F} = \{\mathbf{p}_1, \ldots, \mathbf{p}_Q\}$.

The system model is shown in Fig. 1. In the figure, the receiver selects the best precoder from the codebook and sends the corresponding index of the precoder to the transmitter for a specific channel realization. Then the transmitter can use the index, fed back from receiver, to decide the precoder for the transmission. Since the codebook has size $Q = 2^B$ and only the feedback of the index is required, we can adapt the precoder to the instantaneous channel realization with the cost of the feedback overhead being B bits per feedback.

III. Proposed Codebook Design for Precoding-Aided SM-MIMO Systems

A. Description of the Lloyd Algorithm

To design an effective codebook, we utilize the concepts of the Lloyd algorithm from vector quantization [13]. The idea of the Lloyd algorithm is to optimize the codebook gradually using two criteria with a training set composed of training symbols. For our case, the training symbols are the samples of channel realizations. In the algorithm, given a codebook and training set, we first partition the training set by assigning each training symbol a best codeword. This is the nearest neighborhood criterion. Then, since all codewords are intended to be optimal in their corresponding partitions, we optimize the codewords accordingly, which is called the centroid criterion. Since the codewords are altered after the use of the centroid criterion, the assignment of the codewords to the training symbols should be updated by using the nearest neighborhood criterion again. In so doing, given a representative training set composed of channel realizations,[2] an effective codebook can be attained by iteratively using these two criteria, i.e., we improve the codebook by iteratively partitioning the training set according to the codebook and optimizing the codebook according to the partition results. In the following, we derive the criteria for designing the codebook in SM-MIMO systems.

B. Proposed Codebook Design Algorithm

Considering the maximum likelihood (ML) detection [14], the BER can be tightly bounded in medium and high SNR regimes by the union bound [15], expressed as

$$P_e \le f(\mathbf{p}_k, \mathbf{H}) = \sum_{i=1}^{N_c} \sum_{j=1, i\neq j}^{N_c} \frac{N(i,j) Q\left(\sqrt{\frac{\rho}{2}\left\|\mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j)\right\|^2}\right)}{N_c \log_2 N_c}, \quad (4)$$

[2]A representative training set can sufficiently and statistically represent the practical channel where the designed codebook is to be used.

where $Q(.)$ is the Q-function and $N(i,j)$ is the number of bits in error if $\mathbf{x}_i$ is incorrectly detected as $\mathbf{x}_j$. Therefore, we consider to design the codebook using

$$\min_{\mathcal{F}} E_{\mathbf{H}} \left\{ \min_{\mathbf{p}_k \in \mathcal{F}} f(\mathbf{p}_k, \mathbf{H}) \right\}. \quad (5)$$

Assume that we have a representative training set. To acquire the effective codebook, we first derive the nearest neighborhood criterion. Observing (5), the nearest neighborhood criterion, which is to select the best codeword from a given codebook, should be given by

$$\mathbf{H} \in \mathcal{A}_k \text{ if } f(\mathbf{p}_k, \mathbf{H}) \le f(\mathbf{p}_l, \mathbf{H}), \qquad \forall k \neq l, \quad (6)$$

where $\mathcal{A}_k$ is the set comprised of the channel realizations that should select codeword k. Besides, to provide a simpler criterion, the alternative option is to use the maximum minimum Euclidean distance since the maximization of the minimum Euclidean distance can effectively minimize the BER [7]. The alternative nearest neighborhood criterion is then given by

$$\mathbf{H} \in \mathcal{A}_k \text{ if } \min_{i\neq j} \left\|\mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j)\right\|^2 \ge \min_{i\neq j} \left\|\mathbf{H}(p_{i,l}\mathbf{x}_i - p_{j,l}\mathbf{x}_j)\right\|^2, \quad \forall k \neq l. \quad (7)$$

Now, we derive the centroid criterion. Assume there are subsets $\mathcal{A}_1, \mathcal{A}_2, \ldots, \mathcal{A}_Q$ of channel realizations constructed by using the nearest neighborhood criterion. Since each codeword has an unique subset, we optimize all codewords sequentially to generate a new codebook. To optimize the codeword, we initially consider

$$\begin{aligned} \min_{\mathbf{p}_k} \quad & E_{\mathbf{H}\in\mathcal{A}_k}\{f(\mathbf{p}_k, \mathbf{H})\} \\ \text{subject to} \quad & \|\mathbf{p}_k\|^2 \le MN_t. \end{aligned} \quad (8)$$

Note that the expectation is only obtained over the channel realization subset of the corresponding codeword and we consider the average power constraint being MN_t without loss of generality. Since (8) is generally intractable due to the complicated Q-function and irregular channel realization subset, we consider to simplify and approximate (8). Observe that Q-function can be alternatively expressed as [16]

$$Q(x) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \exp\left(\frac{-x^2}{2\sin^2\phi}\right) d\phi, \quad (9)$$

where exp(.) is the exponential function. We can lower bound $E_{\mathbf{H}\in\mathcal{A}_k}\{f(\mathbf{p}_k, \mathbf{H})\}$ as follows:

$$\begin{aligned} & E\{f(\mathbf{p}_k, \mathbf{H})\} \\ &= \sum\sum \frac{N(i,j)\int_0^{\frac{\pi}{2}} E\left\{\exp\left(\frac{-\rho\|\mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j)\|^2}{4\sin^2\phi}\right)\right\} d\phi}{\pi N_c \log_2 N_c} \\ &\ge \sum\sum \frac{N(i,j)\int_0^{\frac{\pi}{2}} \exp\left(E\left\{\frac{-\rho\|\mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j)\|^2}{4\sin^2\phi}\right\}\right) d\phi}{\pi N_c \log_2 N_c} \\ &= \sum_{i=1}\sum_{j=1, i\neq j} \frac{N(i,j) Q\left(\sqrt{\frac{E\left\{\rho\|\mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j)\|^2\right\}}{2}}\right)}{N_c \log_2 N_c}. \end{aligned} \quad (10)$$

Note that, in (10), the inequality is due to the Jensen's inequality and all the expectations are over the subset $\mathcal{A}_k$. From (10), we can observe that, if there is an approach that can simultaneously minimize the lower bound and the difference between the lower bound and union bound in (10), this approach can acquire effective solution for (8).

To find this approach, we need to characterize the difference between the lower bound and union bound in (10). We therefore define

$$\epsilon_{ij} = \left| E\left\{ \exp\left(\frac{-\rho \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2}{4\sin^2\phi} \right) \right\} - \exp\left(E\left\{ \frac{-\rho \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2}{4\sin^2\phi} \right\} \right) \right|^2. \quad (11)$$

To characterize ϵ_{ij}, we consider a d_{ij} such that

$$0 \le d_{ij} \le \frac{\rho \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2}{2} \quad (12)$$

without loss of generality. Due to the convexity of the exponential function, there must exist a point $c \ge d_{ij}$ such that

$$\exp\left(\frac{-d_{ij}}{2\sin^2\phi} \right) \ge \exp\left(\frac{-c}{2\sin^2\phi} \right) = E\left\{ \exp\left(\frac{-\rho \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2}{4\sin^2\phi} \right) \right\} \quad (13)$$

for any $0 < \phi \le \pi/2$. In addition, we know that

$$d_{ij} \le E\left\{ \frac{\rho \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2}{2} \right\}. \quad (14)$$

This leads to

$$\exp\left(\frac{-d_{ij}}{2\sin^2\phi} \right) \ge \exp\left(E\left\{ \frac{-\rho \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2}{4\sin^2\phi} \right\} \right). \quad (15)$$

Combining (13) with (15), we then have

$$\left| E\left\{ \exp\left(\frac{-\rho \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2}{4\sin^2\phi} \right) \right\} - \exp\left(E\left\{ \frac{-\rho \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2}{4\sin^2\phi} \right\} \right) \right| \le \exp\left(\frac{-d_{ij}}{2\sin^2\phi} \right). \quad (16)$$

With (16) being related to ϵ_{ij}, we consider to minimize the difference between the union bound and the lower bound in (10) by maximizing the minimal d_{ij}. This is similar to the minimization of the maximal square error of all samples if we consider each ϵ_{ij} with a specific ϕ as a sample. To maximize the minimal d_{ij}, we employ the maximization of

$$\min_{\forall i,j,i\neq j} E_{\mathbf{H}\in\mathcal{A}_k} \left\{ \rho \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2 \right\}. \quad (17)$$

Interestingly, the maximization of (17) could also improve the lower bound of (10) because Q-function is monotonically decreasing. Therefore, we consider to minimize the lower bound in (10) and the difference between the lower bound and union bound in (10) simultaneously by using

$$\begin{aligned} \max_{\mathbf{p}_k} \min_{\forall i,j,i\neq j} \quad & E_{\mathbf{H}\in\mathcal{A}_k} \left\{ \left\| \mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2 \right\} \\ \text{subject to} \quad & \|\mathbf{p}_k\|^2 \le MN_t. \end{aligned} \quad (18)$$

We then exploit (18) instead of (8) to optimize the codeword. By defining $\mathbf{R}_k = E_{\mathbf{H}\in\mathcal{A}_k}\{\mathbf{H}^H\mathbf{H}\}$, (18) can then be equivalently expressed as

$$\begin{aligned} \max_{\mathbf{p}_k} \min_{\forall i,j,i\neq j} \quad & \left\| (p_{i,k}\mathbf{c}_{i,k} - p_{j,k}\mathbf{c}_{j,k}) \right\|^2 \\ \text{subject to} \quad & \|\mathbf{p}_k\|^2 \le MN_t, \end{aligned} \quad (19)$$

where $\mathbf{c}_{i,k} = \mathbf{R}_k^{1/2}\mathbf{x}_i$. The (19) is then considered as the centroid criterion for optimizing the codeword; its effective solution can be acquired by using the iterative algorithm in [7]. Finally, with the concept of the Lloyd algorithm, the codebook for the SM-MIMO systems can be effectively designed by iteratively using (7) and (19). The design procedure is summarized in Table I.

TABLE I
PROCEDURE OF THE PROPOSED CODEBOOK DESIGN

Step 1.	Construct the training set.
Step 2.	Set the initial codebook $\mathcal{F}_0$. Set $k = 0$
Step 3.	Given the codebook $\mathcal{F}_k$, create the subsets using the neasrest neighborhood condition in (7).
Step 4.	Given the subsets, generate the optimized codebook $\mathcal{F}_{k+1}$ using the centroid condition (19).
Step 5.	Test whether the iteration converges. If yes, terminate the iteration; otherwise go to Step 3 and set $k = k + 1$.

C. Codeword Selection of the Codebook

As the codebook is effectively designed and known at both the transmitter and receiver, the receiver needs to select the best codeword according to the instantaneous channel realization. In this work, the codeword selection is performed by using the nearest neighborhood criterion. Therefore, if (6) is adopted, the selected codeword $\mathbf{p}_s$ is given by

$$\mathbf{p}_s = \arg\min_{\mathbf{p}_k} f(\mathbf{p}_k, \mathbf{H}). \quad (20)$$

The (20) is to select the codeword which provides the best BER. However, it requires to compute the complicated Q-function. Therefore, alternatively we use the simpler criterion (7), and the selected codeword $\mathbf{p}_s$ is

$$\mathbf{p}_s = \arg\max_{\mathbf{p}_k} \min_{i\neq j} \left\| (\mathbf{H}(p_{i,k}\mathbf{x}_i - p_{j,k}\mathbf{x}_j) \right\|^2. \quad (21)$$

Note that (21) is equivalent to selecting the codeword with maximal minimum Euclidean distance.

IV. Numerical Results

Here we evaluate the proposed codebook design via simulations. We use uncorrelated Rayleigh fading channels; adopt 6000 random channel realizations to construct training set; and evaluate BER with ML detectors. Note that the proposed codebook design is feasible and expected to be effective in channels other than the uncorrelated Rayleigh fading channels. In the figures, we compare the proposed design with the design directly extended from the random vector selection in [8]

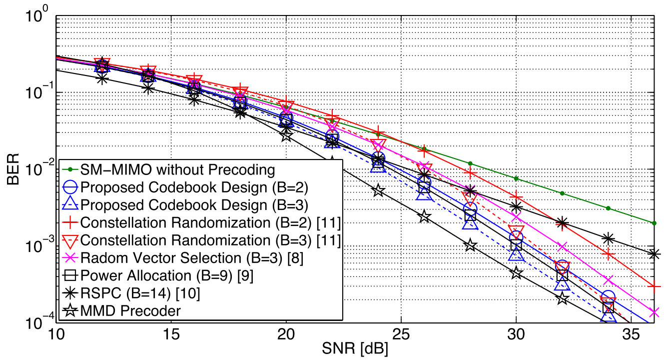

Fig. 2. BER evaluation of different designs for SM-MIMO systems with $N_t = 8$, $N_r = 1$, and $M = 4$ (QPSK) in uncorrelated Rayleigh fading channels.

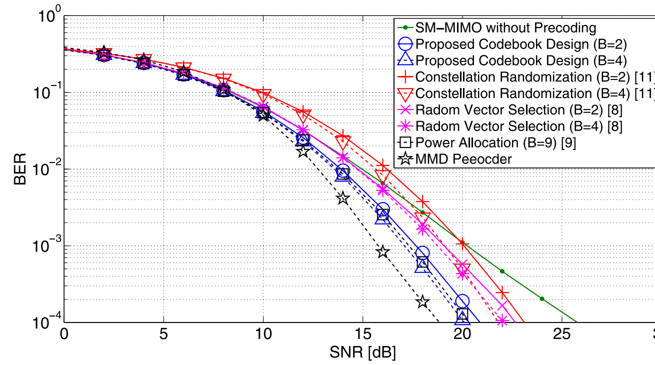

Fig. 3. BER evaluation of different designs for SM-MIMO systems with $N_t = 8$, $N_r = 2$, and $M = 4$ (QPSK) in uncorrelated Rayleigh fading channels.

and the designs in [9]–[11]. Besides, the SM-MIMO systems without precoding and with MMD precoding in [7] are plotted as the references. We note that in the figures, B denotes the required feedback rates.

We employ the SM-MIMO systems with $N_t = 8$, $N_r = 1$ and $M = 4$ (QPSK) in Fig. 2, where we observe that, with a low feedback rate, the proposed design can significantly improve the baseline SM-MIMO system (i.e., no precoding) with certain diversity and coding gain. Besides, comparing the proposed codebook design with other limited feedback precoder designs, the proposed design demonstrates the better BER and lower feedback. The reasons are as follows. As compared to the random vector selection [8] and constellation randomization [11], the proposed design can gradually optimize the codebook with the careful consideration of the relationships between codewords. As compared to the power allocation approach in [9], the proposed design can jointly manipulate all the space-signal symbols with both the phase and power allocation while the design in [9] can only manipulate part of the space-signal symbols with power allocation. As compared to the design in [10], the proposed design exploits both the phase and power allocation to improve the systems. This leads to the potentially better performance. In Fig. 3, the SM-MIMO systems with $N_t = 8$, $N_r = 2$ and $M = 4$ (QPSK) are adopted, and similar results as in Fig. 2 can be observed. The proposed design can effectively improve the systems without precoding and outperform other limited feedback precoder designs. Note that the design in [10] is not included in Fig. 3 because it mainly focuses on the case with $N_r = 1$ and the superiority of the proposed design has been demonstrated in Fig. 2. From Figs. 2 and 3, it can be observed that the performance gap between the proposed design and the MMD precoder can be within 1.5 dB as the proposed design requires only a low feedback overhead. This shows the efficacy of the proposed design. In addition, the results in the figures show that there is a inherent trade-off between BER performance and overhead. This trade-off should be carefully considered in designing the system with limited feedback precoding.

V. Conclusion

In this work, we investigate the limited feedback precoding using codebook and propose an effective codebook design approach for SM-MIMO systems. Via the rationales in Lloyd algorithm, the codebook can be optimized iteratively by using the nearest neighborhood and centroid criteria. These two criteria are explicitly derived in the proposed codebook design to pursue the BER minimization. Numerical results show that the proposed design can significantly improve the baseline SM-MIMO systems with low feedback overhead, and outperform other limited feedback precoder designs.

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