International Journal of Engineering & Extended Technologies Research (IJEETR)

|ISSN: 2322-0163| www.ijeetr.com | A Bimonthly, Peer Reviewed, Scholarly Indexed Journal |

| Volume 8, Issue 2, March - April 2026 |

DOI:10.15662/IJEETR.2026.0802340

Optimal CSI Feedback using Lloyd's Algoritham in a Mimo System

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Publication History: Received: 25.02.2026; Revised: 20.03.2026; Accepted: 25.03. 2026; Published: 28.03.2026.

ABSTRACT: In this paper we study the relation between the ergodic capacity and feedback interval for a Multiple Input Multiple Output (MIMO) system. Based on this relation an optimal feedback interval is derived for the Rayleigh fading channel. The minimum differential feedback rate is also determined for this system considering the channelestimation error and channel quantization distortion.

KEYWORDS: MIMO Systems, Channel State Information (CSI), Lloyd's Quantization Algorithm, Differential Feedback, Ergodic Capacity, Water-Filling Precoding, Rayleigh Fading Channels

I. INTRODUCTION

In MIMO the feedback is creating problems in the transmission of the signal. Channel state information (CSI) feedback problems have been studied intensively due to its potential benefits to the multiple input multiple output (MIMO) systems .CSI can be utilized by a variety of channel adaptive techniques (e.g., water-filling, beamforming, zero-forcing, interference alignment, etc.) at the transmitter side to enhance the spectral efficiency as well as the robustness, especially for systems operating in the frequency division duplexing (FDD) mode. As the capacity of the feedback channel is normally limited, the infinite feedback of CSI is hard to realize in practice. Therefore, it is important to investigate how to decrease the amount of feedback signal. In our analysis we decrease the feedback with water filling pre-coder and Lloyd's quantization algorithm. The minimum differential feedback rate for time correlated MIMO Rayleigh fading channels is used for estimation of both the channel estimation errors and channel quantization distortion.We calculate the relation between the ergodic capacity and the feedback interval with feedback channel capacity constraint in a periodic differential feedback system. For differential feedback system we use water filling pre-coder and Lloyds' quantization algorithm. In order to optimize the feedback design, the relationship between the system capacity and the feedback rate of CSI was studied. Lower and upper bounds of feedback rate that obtain positive capacity gain in comparison with openloop systems were reported [1] and [2]. The optimal feedback rate in a memoryless periodic feedback scheme was studied in [3] when the CSI is fed back independently at each time. However, the differential feedback with temporal correlation is not taken into account. In this paper, we consider a general point-to-point MIMO system with periodic differential CSI feedback over timecorrelated Rayleigh block-fading channels, and investigate the relationship between the capacity and the differential feedback rate with feedback channel capacity constraint.

II. SYSTEM MODEL

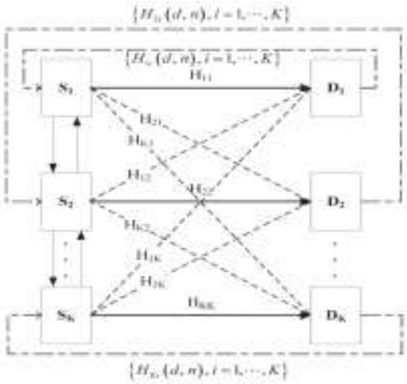

Fig.1 System model of a MIMO Rayliegh fading channel with differential feedback

We consider a *K*-user MIMO system over time correlated block-fading channels, as shown in Fig. 1. Assume that each transmitter S_i, i = 1, 2, . . . , K is equipped with *Nt* antennas and that each receiver D_i, *i* = 1, 2, . . . , K has Nr antennas. The *i*th transmitter *Si* transmits d_i independent spatial data streams to its corresponding receiver D_i. The block-fading channel coefficients $H_{ik}(n)$, i, k = 1, 2, . . . , K are constant throughout the time interval and temporal correlated with each other in different block indexes *n*. The basic system expression is

$$y=H*x+n0 \qquad (1)$$

y denotes a N_r x1 received signal vector, H is a N_r x N_t channel fading matrix with inpendent entries obeying complex Gaussian distribution $CN(0, \sigma_h^2)$ and x represents a N_t x 1 transmitted signal vector . n0 is a N_r x 1noise vector.

III. CHANNEL STATE INFORMATION MODEL

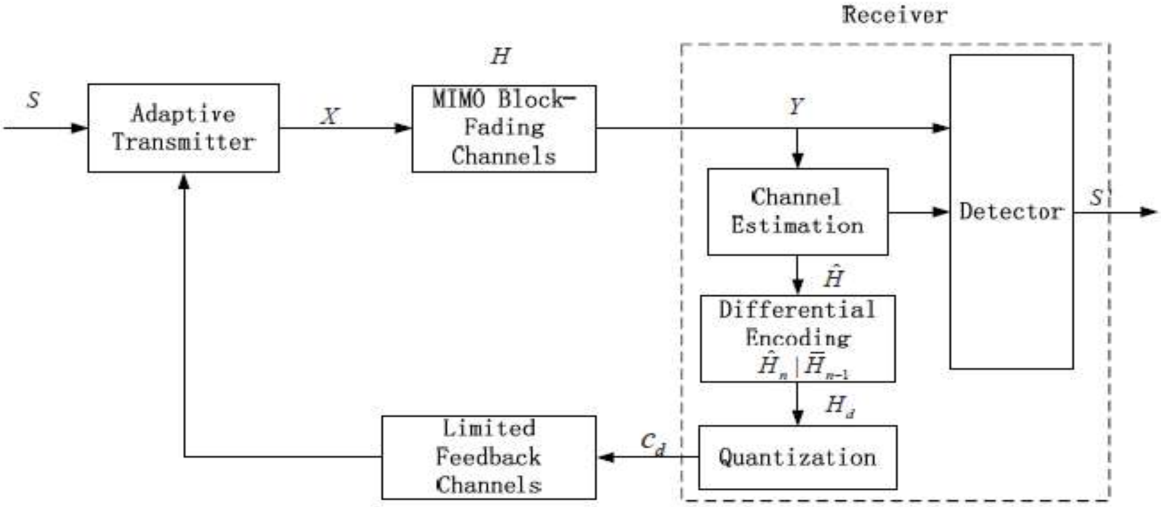

Fig.2 System model of the differential feedback over time-correlated MIMO Rayleigh block-fading channels.

Channel State Information (CSI) is nothing but properties of a communication link. We consider a llimited and error free feedback channel. The channel state information quantization is given by,

$$\hat{H} = \bar{H} + E \qquad (2)$$

Where $\bar{H}$ represents the feedback channel output, E represents an independent additive noise matrix. The quantized CSI can be rewritten as

$$\bar{H} = \frac{\sigma_{\bar{h}}^2}{\sigma_{\hat{h}}^2}\hat{H} + \phi \qquad (3)$$

Where ϕ is independent of $\widehat{H}$ and the entries are i.i.d complex Gaussian variables with $CN\left(0, \frac{\left(\sigma_{\hat{h}}^2 - d\right)d}{\sigma_h^2}\right)$.

We consider the differential feedback, where only the differential CSI will be sent back to the transmitter, assuming that the previous channel quantization matrix $\bar{H}_{n-1}$ is known at both transmitter and the receiver

$$H_d = Diff\left(\hat{H}_{n,}\bar{H}_{n-1}\right) \qquad (4)$$

Diff (.) denotes the differential function. We assume that the CSI feedback channel has a capacity constraint C_{fb} per fading block. When the CSI is quantized to *R* bits and the feedback interval is set as *T* blocks, the average feedback rate satisfies the inequality R/T ≤ C_{fb}. The feedback interval is given by

$$T = \left\lceil \frac{R}{C_{fb}} \right\rceil \qquad (5)$$

This equation denotes the smallest integer larger than x.

IV. ERGODIC CAPACITY OF MIMO SYSTEM

Ergodic capacity refers to the maximum rate that communication can be achieved, assuming the communication duration is longer enough to experience all channel state. At the transmitter, the feedback CSI can be used for precoding to improve the system performance. In this subsection, we utilize the water-filling precoder, which is a common and well-known power allocation scheme to achieve the capacity. However, the analysis and conclusions are also valid for other precoder designs.

With water-filling precoder, the channel quantized CSI is decomposed using singular value decomposition (SVD) at the transmitter as

$$\overline{H} = U \sum V^{+} \qquad (6)$$

Where U and V represent two unitary matrices, and $\sum$ is a non negative and diagonal matrix composed of Eigen values of $\overline{H}$.

For the pilot-assisted MIMO system with ML channel estimation, the closed-loop ergodic capacity employing water filling algorithm can be obtained

$$C_{erg} = E_{\hat{H},\overline{H}}\left[\frac{L-N_t}{L}\log\det\left(IN_r + J.J^{+}(F^{-1})\right)\right] \qquad (7)$$

L denotes the number of transmitted symbols, A denotes the amplitude of signal symbol, and Z stands for a diagonal matrix determined by the water filling algorithm.

V. MIMIMUM DIFFERENTIAL FEEDBACK

We derive the minimum differential feedback rate of the time-correlated MIMO Rayleigh block-fading channels to guarantee the accuracy of CSI. The minimum differential feedback rate is determined by the Shannon’s Rate Distortion Theory of continuous-amplitude sources. The minimum differential feedback rate of the time-correlated MIMO block-fading channels is given by

$$R = N_r N_t . log\left[\alpha^2\left(\frac{\sigma_h^2}{\sigma_{\hat{h}}^2}\right)^2 + \frac{(1-\alpha^2)}{d}\sigma_h^2 + \frac{\sigma_e^2}{d}\left(1+\alpha^2\frac{\sigma_h^2}{\sigma_{\hat{h}}^2}\right)\right] \qquad (8)$$

Where σ_h^2 and $\sigma_{\hat{h}}^2$ denote the variances of h and $\hat{h}$ respectively α is the time correlation coefficient and $N_r and\ N_t$ is number of receiving antenna and transmitting antenna.

From this equation we find that the minimum differential feedback rate is a function of the quantization distortion, time correlation coefficient, and the channel estimation variance. Note that the minimum differential feedback rate from above equation is the lower bound of feedback compression with temporal correlation in the block-fading MIMO channels. Given the accuracy constraint of feedback CSI (i.e., the distortion d), the minimum feedback rate can be easily obtained from above equation.

As the ergodic capacity increases when the distortion decreases, we can investigate the feedback design scheme by minimizing the distortion of the feedback CSI in order to maximize the ergodic capacity. It is obvious that the CSI distortion in the differential feedback model is relevant to the feedback rate and temporal correlation. In addition, large feedback rate and high temporal correlation could reduce the distortion, and thus improve the ergodic capacity.

VI. WATER FILLING PRECODER

Precoding is a generalization of beam forming to support multi-layer transmission in multi antenna wireless communications. In conventional single-layer beam forming, the same signal is emitted from each of the transmit antennas with appropriate weighting such that the signal power is maximized at the receiver output.

When the receiver has multiple antennas, single-layer beam forming cannot simultaneously maximize the signal level at all of the receive antennas. Thus, in order to maximize the throughput in multiple receive antenna systems, multi layer beam forming is required. In point-to-point systems, precoding means that multiple data streams are emitted from the transmit antennas with independent and appropriate weightings such that the link throughput is maximized at the receiver output.

The relations between ergodic capacity and the feedback interval with the feedback capacity constraint using water-filling precoder. It clearly shows that the ergodic capacity is a monotonic Concave function of the feedback interval, and there exists an optimal feedback interval which achieves the maximum ergodic capacity. The reason is given as follows. When T increases from a small region, it begins to provide larger feedback rate, and thus, improves the quality of feedback information. When T goes towards a relatively larger region, the temporal correlation gradually decreases and the feedback delay becomes larger, which causes the feedback information outdated and therefore impairs the performance.

VII. LLOYD QUANTIZATION

It is an algorithm for grouping data points into a given number of categories, used for k-means clustering. Lloyd's algorithm is usually used in a Euclidean distance, so the distance function serves as a measure of similarity between points, and averaging of each dimension for the averaging. Lloyd's algorithm starts by partitioning the input points into k initial sets at random. It constructs a new partition by associating each point with the closest centroid, usually using the Euclidean distance function. Then the centroids are recalculated for the new clusters, and algorithm repeated by alternate application of these two steps until convergence, which is obtained when the points no longer switch clusters.

In our project, the message bit is partitioning into n number of packets such as C message bit into a M regions A_1, A_2,….A_M where A_i denoting cluster regions of the codebook. For optimality of the codebook (to minimize the value of distortion), quantize with smallest Euclidean distance. For every M regions we will continue above process.

In our analysis, Lloyd’s quantization algorithm is based on differential function. It depends on Shannon’s rate distortion theory. This will execute in four steps. First make the statistics of the both transmitter and receiver. In second step we conclude the current differential channel state information. Afterwards in third step quantize as differential codebook with smallest Euclidian distance to it. In the fourth step the corresponding code word sent to the transmitter.

VIII. RESULTS AND DISCUSSIONS

In this section, we first provide the simulation results for the derived minimum differential feedback rate expression.

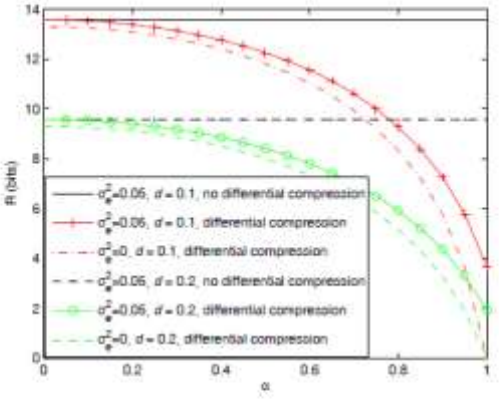

Fig.3. The relationship between the minimum differential feedback rate and time correlation for Nr = 2, Nt = 2, $\sigma 2\ e$ = 0, 0.05, and d = 0.1, 0.2.

Then, we discuss the relations between the ergodic capacity and the feedback interval in a periodic differential feedback system with feedback channel capacity constraint. Finally, we verify our theoretical results by a practical differential feedback system employing water-filling precoder and Lloyd’s quantization algorithm. All simulations are performed for a general point-to-point MIMO system over time-correlated block fading channels. For simplicity and without loss of generality, we use Nt = 2 transmit antennas and Nr = 2 receive antennas, and the channel variance is set as $\sigma 2\ h$ = 1.

A. Minimum Differential Feedback Rate Figure 3 illustrates the minimum differential feedback rate versus the temporal correlation. The simulation parameters are selected as follows. The value of channel estimation error $\sigma 2\ e$ is selected as 0 for the case of ideal channel estimation and 0.05 for a typical case of practical channel estimation in a medium SNR case (e.g., SNR = 6 dB) [4]. The quantization distortion d is selected as 0.1 and 0.2 approximately corresponding to 10-bit and 14-bit quantization for 2 × 2 MIMO channels [3], respectively. For comparison, we also include the nondifferential compression results in Fig. 3 which is defined as a strategy that feeds back CSI independently with the previous quantization CSI. The lower bound of the non-differential feedback rate can be found in [1] and [3]. From Fig. 3, we can see that when temporal correlation increases, it results in significant reduction of feedback rate by using differential compression. In addition, the impact of estimation error and quantization distortion is also illustrated in Fig. 2. For lower quantization distortion, higher feedback rate is required. It can be also observed from Fig. 2 that with more estimation errors, the feedback rate increases. Especially, when the time correlation coefficient is $\alpha = 1$, the channel coefficient is a constant. If there is no estimation error, we get that ˆHn = Hn = H$n-1$ = ˆH$n-1$ is also a constant. For this case, the previous quantization CSI is sufficient to preserve the accuracy of CSI at the transmitter, and thus no differential feedback bits are required. However, if the estimation error exists, the estimation channel ˆHn ≠ ˆH$n-1$ is no long a constant. Therefore, additional differential feedback bits are required to guarantee the accuracy of CSI at the transmitter. These observations can be well explained by (5).

Ergodic Capacity and Feedback Interval:

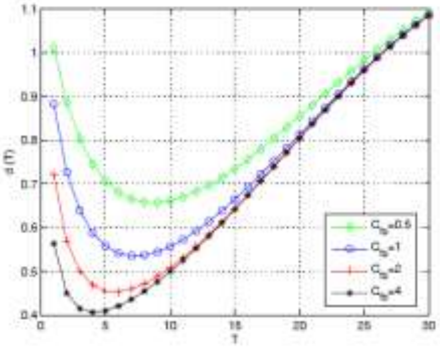

Fig. 4. The relationship between the distortion of CSI and the feedback interval for Nr = 2, Nt = 2, $\sigma 2$ h = 1, and $\sigma 2$ ˆh = 1.2.

In this subsection, we give the simulation results of the relationship between the ergodic capacity and the feedback intervals. For simplicity, we assume that the block size is L = 100 of duration relatively smaller value of SNR, which is 0 dB, and the Doppler frequency is 9.26 Hz, corresponding to 5 km/h moving speed and 2 GHz carrier frequency. Note that higher SNR and more pilot power result in lower estimation error, which also causes lower differential feedback rate. Given L = 100, μ = 10%, and SNR = 0, we can obtain that the variance of channel estimation is $\sigma 2$ ˆh = 1.2 with the help of [23]. Figure 3 illustrates the distortion of CSI in (3) versus the feedback interval with different feedback capacity constraint Cfb = {0.5, 1, 2, 4} for every fading block. From Fig. 4, we can see that the CSI distortion is a convex function of feedback intervals given a feedback constraint and there exists an optimal feedback interval to minimize the distortion.

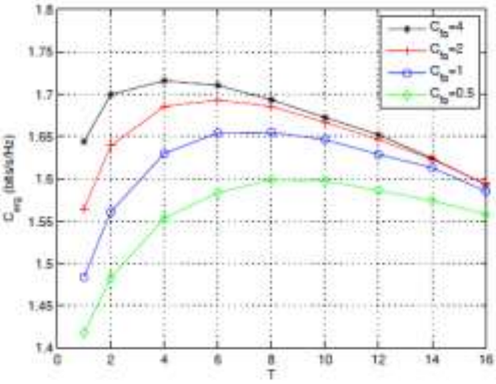

Fig. 5. The relationship between the ergodic capacity and feedback interval for Nr = 2, = 2, SNR = 0 dB, L = 100, and fD = 9.26 Hz.

In Fig. 4, we show the relations between ergodic capacity and the feedback interval with the feedback capacity constraint Cfb = {0.5, 1, 2, 4} using water-filling precoder. It clearly shows that the ergodic capacity is a monotonic concave function of the feedback interval, and there exists an optimal feedback interval which achieves the maximum ergodic capacity. The reason is given as follows. When T increases from a small region, it begins to provide larger feedback rate, and thus, improves the quality of feedback information. When T goes towards a relatively larger region, the temporal correlation gradually decreases and the feedback delay becomes larger, which causes the feedback information outdated and therefore impairs the performance.

IX. CONCLUSION

In this paper, we have derived the minimum differential feedback rate for the time-correlated Rayleigh block-fading channels considering channel estimation errors, which is the lower bound of feedback compression with temporal correlation. Furthermore, provided the feedback-channel constraint Cfb per fading block, the relationship between the ergodic closed-loop capacity and the feedback interval is investigated in this paper. We find that the ergodic closed-loop capacity is a monotonic concave function of the feedback interval and there exists an optimal feedback interval to achieve the maximum ergodic capacity. Simulation results of a practical differential feedback system with water-filling precoder and Lloyd’s quantization algorithm are provided to validate our theoretical results.

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