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Implementation of Multiuser MIMO System using Quantized CSI-Based Tomlinson-Harashima Precoding

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Abstract: This paper considers the implementation of Tomlinson-Harashima (TH) pre-coding for multiuser MIMO systems based on quantized channel state information (CSI) at the transmitter side. Compared with the results in, our scheme applies to more general system setting where the number of users in the system can be less than or equal to the number of transmit antennas. We also study the achievable average sum rate of the proposed quantized CSI-based TH pre-coding scheme. The expression of an upper bound on the mean loss in sum rate due to CSI quantization is derived. We also present some numerical results. Both the analytical and numerical results show that nonlinear pre-coding suffers from imperfect CSI more greatly than linear pre-coding. Nonlinear TH pre-coding can achieve much better performance than that of linear zero-forcing pre-coding for both perfect CSI and quantized CSI cases. In addition, our derived upper bound on the mean rate loss for TH pre-coding converges to the true rate loss faster than that of zero-forcing pre-coding obtained in as the number of feedback bits becomes large. Both the analytical and numerical results show that nonlinear pre-coding suffers from imperfect CSI more than linear pre-coding does obtained as the number of feedback bits increases.

Keywords: Tomlinson-Harashima Pre-Coding, QR Decomposition, Random Vector Quantization, Zero-Forcing, Givens Transformation.

I. INTRODUCTION

Since the pioneering work and, multiple-input multiple-output (MIMO) communication systems have been extensively studied in both academic and industry communities and becomes the key technology of most emerging wireless standards. It is shown that significantly enhanced spectral efficiency and link reliability can be achieved compared with conventional single antenna systems. In the downlink multiuser MIMO systems, multiple users can be simultaneously served by exploiting the spatial multiplexing capability of multiple transmit antennas, rather than trying to maximize the capacity of a single-user link. The performance of a MIMO system with spatial multiplexing is severely impaired by the multi-stream interference due to the simultaneous transmission of parallel data streams. To reduce the interference between the parallel data streams, both the processing of the data streams at the transmitter (pre-coding) and the processing of the received signals (equalization) can be used. Pre-coding matches the transmission to the channel. Accordingly, linear pre-coding schemes with low Givens transformation. Complexity is based on zero-forcing (ZF) or minimum mean-square-error (MMSE) criteria and their improved version of channel regularization. In spite of very low complexity, the linear schemes suffer from capacity loss. Nonlinear processing at either the transmitter or the receiver provides an alternative approach that offers the potential for performance improvements over the linear approaches. This kind of approaches includes schemes employing linear pre-coding combined with decision feedback equalization (DFE), vector perturbation, Tomlinson-Harashima (TH) pre-coding, and ideal dirty paper coding which is too complex to be implemented in practice.

The optimal solution with an exhaustive search over all possible integers in the lattice is complexity prohibited. Although some sub-optimal solutions, such as sphere encoder, exist, the complexity is still much higher than TH precoding.TH pre-coding can be viewed as a simplified version of vector perturbation by sequential generation of the integer offset vector instead of joint selection. This technique employs modulo arithmetic and has a complexity comparable to that of linear pre-coders. It was originally proposed to combat inter-symbol Interference in highly dispersive channels and can readily be extended to MIMO channels. Vector perturbation has been proposed for multiuser MIMO channel model and can achieve rate near capacity. It has superior performance to linear pre-coding techniques, such as zero-forcing beam forming and channel inversion, as well as TH pre-coding. However, this method requires the joint selection of a vector perturbation of the signal to be transmitted to all the receivers, which is a multidimensional integer-lattice least-squares problem. Although it was shown that TH pre-coding does not perform nearly as well as vector perturbation for general SNR regime, it can achieve significantly better performance than the linear pre-processing algorithm, since it limits the transmitted power increase while pre-eliminating the inter-stream interference. Thus, it provides a good choice of trade-off between performance and complexity and has recently received much attention. Note that TH pre-coding is strongly related to dirty paper coding.

In fact, it is a suboptimal implementation of dirty paper coding proposed. As many pre-coding schemes, the major problem for systems with TH pre-coding is the availability of the channel state (CSI) information at the transmitter. In time division duplex systems, since the channel can be assumed to be reciprocal, the CSI can be easily obtained from the channel estimation during reception. In frequency division duplex (FDD) systems, the transmitter cannot estimate this information and the CSI has to be communicated from the receivers to the transmitter. In this work, we design a spatial TH-pre-coder based on minimizing the sum-MSE of the individual users (MMSES-THP) due to its mathematical tractability. Based on the available statistics of the CMI and the quantized CDI, received error-free but quasi-instantaneously, the optimum feed forward filter as well as the optimum feedback filter is computed at the transmitter. Additionally, a near optimal pre-coding order is found with a reduced complexity based on the derived filters. In MMSE-S-THP based on imperfect CSI where the quantization is performed using scalar quantization has been proposed. In, the MMSE-THP was derived based on an estimated CSI. To the best of our knowledge, an MMSES-THP based on quantized CDI using the RVQ scheme has not been yet investigated. As many pre-coding schemes, S-THP requires that perfect CSI has to be available at the transmitter so that the pre-coder is matched to the channel.

However, perfect CSI is an unrealistic assumption in FDD systems. Due to independent channels in the DL and in the uplink (UL) in FDD systems, CSI is relayed to the transmitter through a dedicated limited feedback channel. The K users first estimate their DL channels with a common DL pilot. Each of the K users then quantizes its CDI - for instance using random vector quantization (RVQ) scheme - with B feedback bits which are relayed back to the transmitter. Hence, the latter has only access to a quantized version of the estimated CDI and to the statistics of the Channel Magnitude Information (CMI) of each user as transmit CSI. TH pre-coding can be viewed as a simplified version of vector perturbation by sequential generation of the integer offset vector instead of joint selection. This technique employs modulo arithmetic and has a complexity comparable to that of linear pre-coders. It was originally proposed to combat inter symbol interference in highly dispersive channels and can readily be extended to MIMO channels [2]. Although it was shown in [11] that TH pre-coding does not perform nearly as well as vector perturbation for general SNR regime, it can achieve significantly better performance than the linear pre-processing algorithm, since it limits the transmitted power increase while pre-eliminating the inter-stream interference [12]. Thus, it provides a good choice of tradeoff between performance and complexity and has recently received much attention [2, 12]. Note that TH pre-coding is strongly related to dirty paper coding. In fact, it is a suboptimal implementation of dirty paper coding proposed. As many pre-coding schemes, the major problem for systems with TH pre-coding is the availability of the channel state information (CSI) at the transmitter. In time division duplex systems, since the channel can be assumed to be reciprocal, the CSI can be easily obtained from the channel estimation during reception.

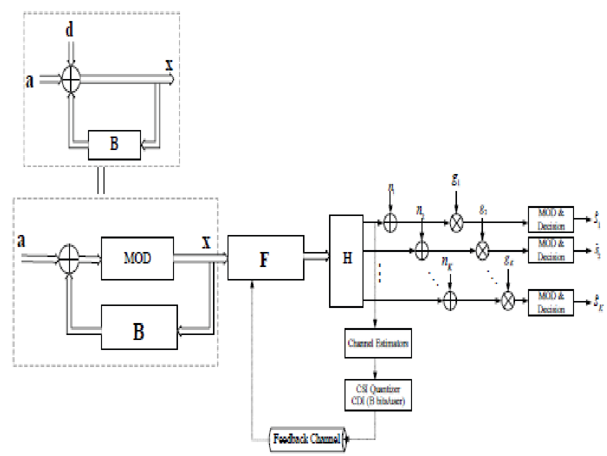

Fig.1.TH pre-coding for multiuser MIMO downlink with quantized CSI feedback.

In frequency division duplex (FDD) systems, the transmitter cannot estimate this information and the CSI has to be communicated from the receivers to the transmitter via a feedback channel. In this paper, we will focus on the implementation of TH pre-coding in FDD systems. In this context, for linear pre-coding, there have been extensive research results for MIMO systems with quantized CSI at the transmitter [3]. However, as far as we know, there has been very few works directed at the design of TH pre-coding based on the quantized CSI at the transmitter side. In this respect, the previous design it is based on MMSE criteria. Since the MSE is a function of both statistics (moments) of the channels and the statistics of the channel quantization error, the computation of the MSE requires the exact distribution of the channels which can be very difficult to obtain in practical systems. In addition, even if the exact distribution function of channels could be obtained, the statistics of quantization error can be very difficult to obtain for more general channel fading other than uncorrelated Rayleigh fading even with simple random vector quantization (RVQ) codebook. Instead, we aim to design low complexity method which can be easily implemented in practical systems with arbitrary channel fading. Our scheme employs a more direct method which only depends on the quantized CDI of user channels.

A transmitter equipped with multiple antennas communicates with a receiver that has multiple antennas. Most classic pre-coding results assume narrowband, slowly fading channels, meaning that the channel for a certain period of time can be described by a single channel matrix which does not change faster. In practice, such channels can be achieved, for example, through OFDM. Pre-coding strategy that maximizes the throughput called channel capacity depends on the channel information**.** In this paper, we design a multiuser spatial TH pre-coding based on quantized CSI and ZF criteria. As in [2], we focus on high spectral efficiency, in particular non-binary modulation alphabets and correspondingly we assume high signal-to-noise ratios (SNRs). In contrast to [2] where perfect CSI is at the transmitter side, we assume only quantized CDI is available at the transmitter. The feed forward filters as well as the feedback filter are computed at the transmitter only based on the available quantized CDI at the transmitter side. In addition, our scheme also generalizes the results in [2] to more general system setting where the number of users K in system can be less than or equal to the number of transmit antennas n_T.

II. MIMO CAPACITY WITH CHANNEL STATE

Systems with multiple transmit and receive antennas can increase the spectral efficiency and the supported data rates dramatically. In a broadcast (BC) scenario, i.e., the DL in a MU-MISO system, employing M antennas at the transmitter (e.g. the Base Station) and K decentralized receivers (e.g. mobile user terminals) with a single antenna each, and motivated by the need of simple receivers, transmit processing, i.e. pre-coding, has to be performed at the transmitter. Linear pre-coding, e.g. Zero Forcing (ZF) and Minimum MSE (MMSE), has been investigated for such systems due to its simplicity. Alternatively, non-linear pre-coding has received attention due to the increased throughput obtained as compared to the linear pre-coding. Tomlinson Harashima pre-coding belongs to a class of successive and non-linear pre-coding schemes where the already pre-coded symbols are fed back and the spatial interference is suppressed with a non-linear modulo operator. In, the existing multiuser MIMO algorithm is extended to MIMOOFDM systems by joint power allocation across OFDM subcarriers and interpolating the pre-coding and decoding matrices corresponding to different OFDM subcarriers. In, an iterative algorithm between transmit beam forming and receive beam forming is developed.

However, none of these studies addresses robust pre-coder design with reduced feedback in MU MIMO-OFDM. The research results in MU-MIMO can be readily extended to multiuser multiple-input multiple-output orthogonal frequency division multiplexing (MU MIMO-OFDM) systems in frequency-selective fading channels by regarding the signal model on each subcarrier as a traditional MU-MIMO. In this thesis, two categories of low-complexity pre-coding algorithms are proposed to reduce the computational complexity and improve the performance of BD-type pre-coding algorithms. One is based on multiple LQ decompositions and lattice reductions. The other one is based on a channel inversion technique, QR decompositions, and lattice reductions to decouple the MU-MIMO channel into equivalent SU-MIMO channels. Both of the two proposed pre-coding algorithms can achieve a comparable sum-rate performance as BD-type pre-coding algorithms, substantial bit error rate (BER) performance gains, and a simplified receiver structure, while requiring a much lower complexity. Block diagonalization (BD)-type based pre-coding techniques are well-known linear pre-coding strategies for MU-MIMO systems. By employing BD-type pre-coding algorithms at the transmit side, the MU-MIMO broadcast channel is decomposed into multiple independent parallel SU-MIMO channels and achieves the maximum diversity order at high data rates. The main computational complexity of BD-type pre-coding algorithms comes from two singular value decomposition (SVD) operations, which depend on the number of users and the dimensions of each user's channel matrix.

An optimal dimension compression and restoration algorithm is developed. To circumvent the degradation introduced by the channel feedback errors, we give robust pre-coder designs on both LP and THP by taking the feedback channels as random vectors. Simulation results show the superiority of the robust designs over the non-robust designs. Generally speaking, the brute-force generalization of MUMIMO to MU MIMO-OFDM by feeding back the CSIT from user equipment (UE) to BS on all or parts of subcarriers may lead to huge feedback overhead. In this paper, unlike the traditional frequency-domain feedback approach, a time domain approach is proposed to not only reduce the amount of feedback bits but also take advantage of the channel correlation to construct a more compact feedback vector. In frequency-duplexed systems, where uplink and downlink are apart in frequency, the link fading is not reciprocal and thus the CSI must be conveyed through feedback, which may incur round-trip delays that are non-negligible with respect to the coherence time of the CSI being reported. Consequently, the transmitter is usually deprived of instantaneous CSI.

In time-duplexed systems, in contrast, the links are reciprocal as long as the coherence time of the fading process exceeds the duplex time.1 Thus, the transmitter may have access to reliable CSI at low and moderate levels of mobility. At high levels of mobility, even in time-duplexed systems the CSI becomes rapidly outdated. In terms of the characterization of the single-user capacity, these various scenarios are usually mapped onto distinct operational regimes:

a) The transmitter has instantaneous CSI.
b) The transmitter has only statistical CSI.
c) The transmitter has no CSI.

For regimes (b) and (c), closed-form expressions are available for Rayleigh-faded channels whose entries are IID (independent identically distributed), both for arbitrary numbers of antennas and asymptotically in the number of antennas. Also for correlated Rayleigh-faded channels, analytical characterizations in these regimes abound, for arbitrary numbers of antennas and asymptotically there. These analyses reveal how the corresponding capacities are impacted by antenna correlation. The asymptotic expressions, specifically, turn out to be particularly insightful and very accurate even for small numbers of antennas. For regime (a), on the other hand, the capacity had been analyzed only for channels with IID entries, for arbitrary numbers of antennas and asymptotically. In this paper, we present a more extensive analysis that encompasses correlated channels. Specifically, For arbitrary numbers of antennas, we tightly bound the capacity of uncorrelated Rayleigh-faded channels. The bound, in compact closed-form, becomes exact at high signal-to-noise ratio. Asymptotically in the number of antennas, we find expressions for the capacity of Rayleigh-faded channels with either correlated or uncorrelated entries.

III. MULTI-USER MIMO (MU-MIMO) SYSTEM PRECODING

Compared with the single-user multiple-input multiple output(SU-MIMO) systems, multi-user MIMO (MUMIMO) systems can achieve tremendous capacity gains without requiring additional spatial or spectral resources. Considering the knowledge of the data vector and the channel state information (CSI) at the base station (BS) side, inter-user interference (IUI) can be canceled so that each user only receives its designated data. Several MU-MIMO pre-coding techniques were proposed in the literature in order to achieve the near capacity. To this end, downlink pre-coding techniques based on the information-theoretic concept of dirty paper coding (DPC), first proposed it can be used. Among these techniques the linear pre-coding which consists of pre-processing the data vector using a criterion-based filtering matrix, which is constructed using either the zero-forcing (ZF) or the minimum-mean square error (MMSE) criterion Although the MMSE pre-coding alleviates the noise amplification problem appearing in the case of ZF pre-coding especially when the channel matrix is ill-conditioned, it still performs much worse than the optimum brute-force encoder in terms of bit-error rate (BER) performance and diversity order.

Therefore, linear pre-coding is sufficient to achieve quasi-optimum performance due to the good conditionality of the reduced basis of the channel matrix are extensively used to obtain better bases, where LLL algorithm is shown to require fewer computations than SA for an almost negligible degradation in the BER performance. However, drawbacks of the lattice-reduction-based pre-coding techniques are in their iterative nature that slows down the encoding process, and their high worst-case computational complexity, which is exponential in the case of ill-conditioned channel matrix. To alleviate the noise amplification, lattice-base reduction techniques iteratively find a better-conditioned base, i.e., a channel matrix with shorter and more orthogonal columns. In this work, we design a spatial TH-pre-coder based on minimizing the sum-MSE of the individual users (MMSES-THP) due to its mathematical tractability. Based on the available statistics of the CMI and the quantized CDI, received error-free but quasi-instantaneously, the optimum feed forward filters as well as the optimum feedback filter are computed at the transmitter. Additionally, a near optimal pre-coding order is found with a reduced complexity based on the derived filters. In, an MMSE-S-THP based on imperfect CSI where the quantization is performed using scalar quantization has been proposed. In, the MMSE-THP was derived based on an estimated CSI. To the best of our knowledge, an MMSES-THP based on quantized CDI using the RVQ scheme has not been yet investigated.

A linear version of this technique consists of two stages (i) a vector perturbation (VP) stage, where the data vector is perturbed by an integer-valued vector such that the required transmit power is reduced, and (ii) a pre-coding stage where the perturbed vector is linearly pre-coded using any of the aforementioned linear techniques. Despite of the apparent improvement by the THP, its vector perturbation stage is equivalent to the successive interference cancellation used in the MIMO detection literature, which is not optimum. As such, further reduction in the required transmit power can be achieved once the VP stage is optimized as shown in fig.2. To further improve the performance of MU-MIMO pre-coding without requiring lattice-basis reduction, the Tomlinson-Harashima pre-coding (THP) reduces the required transmit power via employing a non-linear modulus operation.

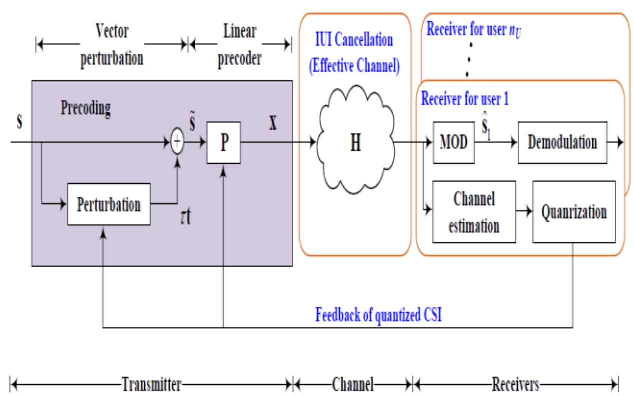

Fig.2. Structure of the MU-MIMO pre-coding system with vector perturbation and imperfect CSI at the transmitter

IV. SIMULATION RESULTS

In this section we present some numerical results. We assume $n_T = K = 4$. Here the SNR of the systems is defined to be equal to P. When the SNR is small and moderate, the average sum rate achieved by quantized CSI-based TH pre-coding can even be better than that of perfect CSI-based linear ZF pre-coding. Fig.3 shows the average sum rate performance of TH pre-coding and linear ZF pre-coding with perfect CSI and quantized CSI, and 4, 8 and 15 feedback bits per user. We can see TH pre-coding performs better than linear pre-coding in both perfect CSI and quantized CSI cases.

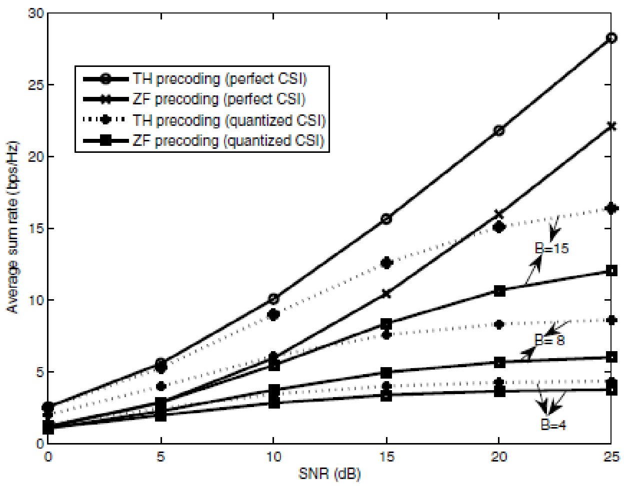

Fig.3. The average sum rate performance of TH pre-coding and ZF pre-coding for both perfect CSI and quantized CSI.

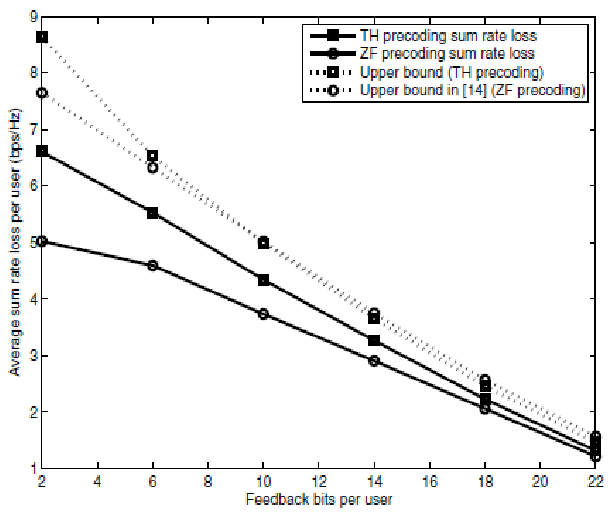

Fig.4.The average sum rate loss per user and corresponding upper bounds against the number of feedback bits. *P* = 25 dB.

Fig. 4 plots the average sum rate loss per user as a function of the number of feedback bits for both ZF pre-coding and TH pre-coding in a system at an SNR of 25 dB. We also plot the upper bound in this paper and the upper bound. From the figure we can see that nonlinear pre-coding suffers from imperfect CSI more than linear pre-coding does. However, the performance of nonlinear pre-coding can still be better than linear pre-coding when SNR is not large or the feedback quantization resolution is high enough. In addition, we notice that the upper bound for TH pre-coding tracks the true rate loss quite closely, and appears to converge faster than the upper bound for linear pre-coding obtained in [4] as *B* increases.

V. CONCLUSION

In this paper, we have investigated the implementation of TH pre-coding in the downlink multiuser MIMO systems with quantized CSI at the transmitter side. In particular, our scheme generalized the results in to more general system setting where the number of users K in the systems can be less than or equal to the number of transmit antennas n_T. In addition, we studied the achievable average sum rate of the proposed scheme by deriving expressions of upper bounds on both the average sum rate and the mean loss in sum rate due to CSI quantization. Our numerical results showed that the nonlinear TH pre-coding could achieve much better performance than that of linear zero-forcing pre-coding for both perfect CSI and quantized CSI cases. In addition, our derived upper bound for TH pre-coding converged to the true rate loss faster than the upper bound for zero-forcing pre-coding obtained in [3] as the number of feedback bits increased.

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