Closed-loop linear dispersion coded eigen-beam transmission and its capacity

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A flexible closed-loop multiple-input-multiple-output (MIMO) system amalgamating linear dispersion codes and eigen-beam transmission is proposed that achieves a higher capacity than the equivalent open-loop scheme, at the cost of feeding back a modest number of feedback bits from the mobile to the base station using Grassmannian beamforming-vector quantisation.

Introduction: The single-stream eigen-beam transmission scheme of [1] achieves significant array gains over open-loop schemes in multiple-input-multiple-output (MIMO) single-user systems, at the cost of feeding back from the mobile station (MS) to the base station (BS) a modest number of bits generated by a Grassmannian beamforming-vector quantiser. The novel contribution of this Letter is that we extend this method to support multiple data streams and hence achieve a higher capacity. Our second contribution is that we amalgamate it with novel LDCs for increasing the attainable diversity gain.

Algorithm: The system having M transmit antennas and N receive antennas investigated in [1] is modelled in the form of $\boldsymbol{y} = \boldsymbol{Hv}s + \boldsymbol{n}$, where $\boldsymbol{y}$ is the received signal, $\boldsymbol{H}$ is an $(N \times M)$-element complex-valued matrix representing the IID Rayleigh channel, $\boldsymbol{v}$ is an $(M \times 1)$-element complex-valued beamforming vector, s is the transmitted symbol at each time instance and $\boldsymbol{n}$ denotes the Gaussian noise. The beamforming vector $\boldsymbol{v}$ is chosen as the channel's eigen-vector corresponding to the highest-power eigen-value denoted as $\boldsymbol{v}_{max}$, in order to achieve the highest possible beamforming gain.

Naturally, the channel is estimated at the MS's receiver and the resultant value of $\boldsymbol{v}$ is fed back to the BS in a practical frequency-division-duplex (FDD) system from the MS using a low-rate uplink (UL) feedback channel. Hence, constructing an efficient quantiser for $\boldsymbol{v}$ becomes important. The quantiser codebook design is treated as a so-called Grassmannian line packing problem in [1], which populates the one-dimensional subspace with as high a number of quantised values as possible, while maximising their minimum distance to avoid their corruption to the immediate neighbours. This mathematical problem is well-documented and the efficiency of this codebook design is demonstrated in [1].

To increase the throughput of their design, the authors of [1] employed spatial multiplexing (SM) in their later work [2], where independent information streams are transmitted over different transmit antennas. They proposed a quantised water-filling aided full eigen-beam transmission scheme using a Grassmannian right-hand-side (RHS) singular-matrix quantiser, stating that finding a good codebook for the RHS singular-matrix quantisation problem is challenging.

Hence, in order to dispense with the RHS singular-matrix at the transmitter, the employment of linear dispersion codes (LDCs) [3] is proposed instead of SM in our study, as illustrated in Fig. 1. By setting the eigen-beamforming vectors to $\boldsymbol{v}_1 = \boldsymbol{v}_{max}$, $\boldsymbol{v}_i = 0$ if $i \in \{2, \ldots, M\}$ and setting the power allocation values to $d_1 = 1$, $d_i = 0$ if $i \in \{2, \ldots, M\}$, the closed-loop full eigen-beamforming scheme is simplified to a single eigen-beam scheme by assigning all power to the most dominant eigen-beam. Before carrying out these operations, the input-shaping matrix $\boldsymbol{V}_C$, where $\boldsymbol{V}_C$ represents the eigenvectors of the covariance matrix of the LDC codeword $\boldsymbol{C}$ is employed in order to spatially decorrelate the input signal so as to disperse the input energy in the most effective way across the LDC's time slots and antennas [4]. LDCs can be designed for arbitrary modulation schemes as well as for an arbitrary number of transmit or receiver antennas, and for diverse numbers of LDC time slots T and data streams Q. Hence they are capable of satisfying diverse design criteria, such as having a higher data-rate than the SM scheme of [5] by setting $Q \geq M$. LDCs are also capable of attaining the maximum achievable diversity order or maximum open-loop capacity etc. [6]. An LDC is specified in the form of LDC(MNTQ)-(modulation-scheme) (e.g. LDC(3224)-QPSK). The LDC-encoded codeword $\mathbf{C}$ is generated as: $\mathbf{C} = \sum_{q=1}^{Q} \mathbf{A}_q s_q$, where the modulated symbols of the independent data streams s_q, $q \in \{1, 2, \ldots, Q\}$ are spatio-temporally dispersed by the LDC dispersion matrices $\boldsymbol{A}_i$, $i \in \{1, 2, \ldots, Q\}$ to all transmit antennas within a codeword duration of T LDC slots. As a result, all the entries in the LDC codeword are constituted by a linear combination of all modulated symbols in the vector $\boldsymbol{s}$. We refer to this property as having non-separable transmit symbols (NSTS). This NSTS property allows us to simplify the water-filling aided full eigen-beam transmission to single eigen-beam transmission at a modest performance degradation, when using the Grassmannian beamforming-vector quantiser.

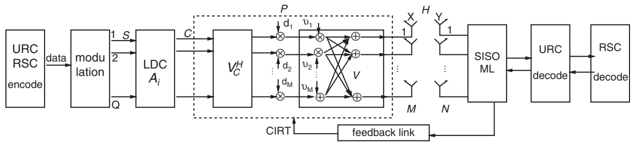

Fig. 1 *Single-user MIMO system models*

Results: Fig. 2 shows the discrete-input-continuous-output memoryless channel's (DCMC) MIMO capacity for an $(M = 3,\ N = 2)$-antenna system using the LDC(3224)-QPSK scheme. When using perfect channel state information at the transmitter (CSIT), the closed-loop single eigen-beam scheme achieves about 4 dB gain over the open-loop scheme, and it performs similarly to the closed-loop full eigen-beam scheme. When using a 3-bit instaneous beamforming vector feedback generated by a Grassmannian beamforming-vector quantiser through an error-free and delay-free feeback channel as our CSIT, the closed-loop single beam scheme achieves an approximately 2 dB gain over the open-loop scheme.

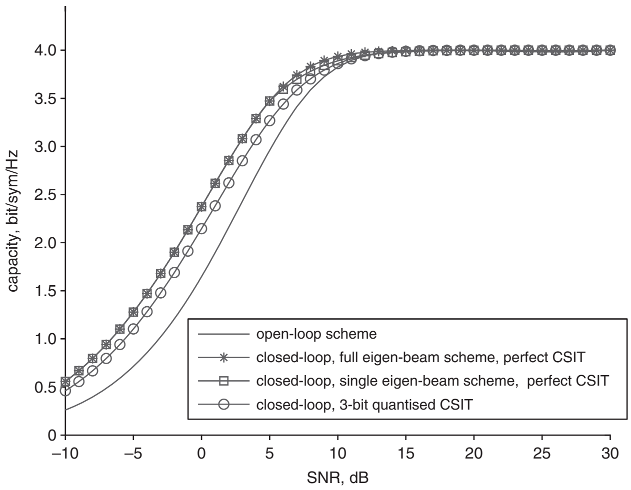

Fig. 2 *DCMC capacity of $M = 3$, $N = 2$ system using LDC(3224)-QPSK and different transmission schemes*

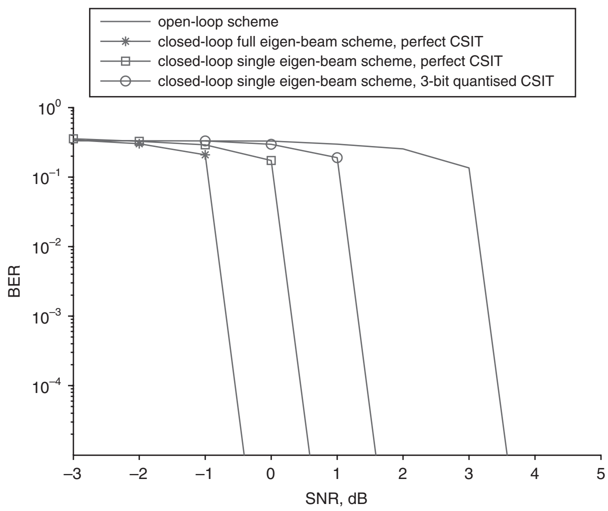

Fig. 3 *BER performance of $M = 3$, $N = 2$ system using LDC(3224)-QPSK and different transmission schemes*

Fig. 3 shows the achievable bit-error-ratio (BER) performance of the same system combining unitary-rate-coding (URC) [7], a half-rate recursive systematic code (RSC) RSC(2,1,5) and a soft-input-soft-output

(SISO) maximum-likelihood (ML) detector. The number of detection iterations was set to $I_{URC} = 1$ between the detector and the URC decoder and $I_{RSC} = 5$ between the detector and the RSC decoder. When assuming perfect CSIT, the closed-loop full eigen-beam scheme and the closed-loop single eigen-beam scheme achieve error-free transmission at about 0 and 1 dB, which are 4 and 3 dB lower than the SNR required by the corresponding open-loop scheme, respectively. Using a 3-bit quantised closed-loop single-beam scheme, a 2 dB gain is attainable compared to the open-loop benchmark scheme.

Conclusion: The amalgamated of LDC and single eigen-beam transmission scheme using the Grassmannian bemforming-vector quantiser is capable of providing a valuable capacity gain, while requiring a modest number of CSIT feedback bits.

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