LIMITED FEEDBACK WITH JOINT CSI QUANTIZATION FOR MULTICELL COOPERATIVE GENERALIZED EIGENVECTOR BEAMFORMING

Ramya Bhagavatula and Robert W. Heath, Jr.
Wireless Networking and Communications Group
The University of Texas at Austin
{bhagavat, rheath}@ece.utexas.edu

Bhaskar Rao
Center for Wireless Communications
University of California, San Diego
brao@ece.ucsd.edu

ABSTRACT

Existing work on limited feedback for cooperative multicell beamforming quantizes the desired and interfering channel state information (CSI) using separate codebooks. In this paper, it is shown that comparatively higher sum-rates can be obtained by jointly quantizing the desired and interfering CSI using a single codebook. A selection criterion is developed for random vector quantization (RVQ) to show that joint quantization with RVQ yields higher sum-rates than those obtained using separate codebooks. The generalized Lloyd algorithm is then used to generate codebooks using the codeword design strategy proposed in this paper. Simulations are used to show that the proposed joint quantization approaches perform almost as well as the full CSI case.

Index Terms— Cooperative systems, Array signal processing, Limited feedback, Channel state information, Joint quantization

1. INTRODUCTION

Cooperation among base stations can be used to deal with co-channel interference and increase the sum-rates in multicell systems [1, 2, 3]. Base stations coordinate their transmissions by sharing control information, transmission signals and/or precoding data over a high-speed backhaul link. The sum-rates obtained in a cellular system can be increased at the cost of greater amount of information shared between base stations. Several transmission strategies are proposed in the literature that offer tradeoffs between performance gains, complexity and overhead [1, 2, 3, 4]. In this paper, we use the cooperative beamforming strategy proposed in [5, 4] that approximately maximizes the sum-rates obtained in a multicell multiple-input single-output (MISO) system by designing beamforming vectors using a generalized eigenvalue decomposition approach.

Achieving the full benefits of coordination requires knowledge of users’ CSI at the base stations or a central control unit. Limited feedback can be used to make coordination practical. Unfortunately, most prior work on limited feedback (see e.g. [6] and the references within) does not take into account the differences in the desired and interfering signal strengths that may considerably change the feedback strategy for multicell systems. In [4], the relative strength of the interfering and desired signals is used to adaptively assign feedback bits to quantize the channels for generalized eigenvector beamforming (GEBF) to approximately minimize the mean loss in sum-rate due to limited feedback. In this paper, we show that comparatively higher sum-rates can be obtained by jointly quantizing the desired and interfering CSI.

This paper derives a new selection criterion for multicell MISO systems, to choose a codeword from a codebook, to approximately minimize the loss in sum-rate due to quantization. The proposed criterion, derived using random vector quantization (RVQ), is a function of the relative strength of the desired and interfering signals. Then, we develop a new codeword design technique to generate codebooks using the generalized Lloyd algorithm (GLA). Simulations are used to show that the sum-rates obtained using the GLA are close to those with full CSI and greater than those of a separate codebook approach. This work supports the design of codebooks that jointly quantize the desired and interfering channels.

Notation: In this paper, $X$ and $y$ refer to a matrix and a vector, respectively. The transpose and Hermitian transpose of $X$ are given by $X^T$ and $X^*$, respectively. $E\{\cdot\}$ refers to the expectation. $\|x\|_2$ stands for the two-norm of $x$. We denote the $n$th element of $x$ by $X(n)$. Finally, $I_N$ denotes an Identity matrix of size $N \times N$.

2. SYSTEM MODEL

Fig. 1 depicts the setup of a linear array of cells used in this paper where each cell has a single active user, using intracell time division multiple access. This setup is based on the Wyner model [7]. Base stations are assumed to have $N_t$ antennas, while the receiver terminals have single antennas. Each user faces interference from one of its neighboring cells. The received powers of the desired and interfering signals are modeled using an approach similar to that adopted in [3], where it was assumed that a user at the cell center receives zero interference. A user at the cell edge receives signals from the base stations of both its own cell and the neighboring cell. The backhaul link used for information exchange between base stations is assumed to be ideal and that the time delay associated with feedback and cooperation is zero.

The number of cells is denoted by $K$, where $K$ goes to
infinity for the Wyner model. The channels corresponding to the desired and interfering signals from the $k$th base station are denoted by $h_k \in \mathbb{C}^{N_t \times 1}$ and $g_k \in \mathbb{C}^{N_t \times 1}$, respectively, for $k \in \{1, \ldots, K\}$. The signal transmitted from the $k$th base station to the $k$th user is denoted by $s_k$, where $\mathbb{E}\{|s_k|^2\} = 1$. The received signal power at the $k$th user is given by $\gamma_k(d)$ and $\gamma_k(i)$ for the desired and interfering signals, respectively, where $\gamma_k(d) = \alpha_k \gamma_k(d)$ for $\alpha_k \in [0, 1]$. Using the narrowband flat-fading model, the baseband discrete time input-output relation for the user in the $k$th cell is given by

$$y_k = \sqrt{\gamma_k(d)} h_k^T f_k s_k \sqrt{\gamma_k(i)} g_{k+1}^T f_{k+1} s_{k+1} + n_k,$$

where $y_k \in \mathbb{C}$ is the received signal at the $k$th user and $f_k \in \mathbb{C}^{N_t \times 1}$ is the beamforming vector at the $k$th base station. Finally, $n_k \in \mathbb{C}$ is complex additive zero-mean white Gaussian noise, with $\mathbb{E}\{|n_k|^2\} = N_o$. The signal to interference noise ratio (SINR) of the $k$th user is given by

$$\text{SINR}_k = \frac{|h_k^T f_k|^2}{\rho_k(d) |g_{k+1}^T f_{k+1}|^2 + 1},$$

where $\rho_k(d) = \frac{\gamma_k(d)}{N_o}$ is the received SNR of the desired signal. The desired and interfering channels are modeled by the Rayleigh fading assumption where each entry is an independent and identically distributed zero-mean unit-variance complex Gaussian variable. The sum-rate of all the users within the system, $R_s$, is expressed as

$$R_s = \sum_k \log_2 (1 + \text{SINR}_k).$$

Maximizing the sum-rate, $R_s$, in (1) requires a joint optimization over all the users in the system, which could lead to high-complexity encoding and decoding algorithms.

3. SEPARATE QUANTIZATION-BASED LIMITED FEEDBACK FOR GEBF

Sum-rate can be approximately maximized at high SINR using generalized eigenvector beamforming proposed in [4], where CSI is shared among only neighboring base stations. The $k$th user feeds back CSI of the desired channel, $h_k$ and the interfering channel, $g_{k+1}$. Adjacent base stations exchange CSI and SNRs ($\rho_k$) of active users so that the $k$th base station has knowledge of both $h_k$ and $g_k$. The beamforming vector, $f_k$, is then computed at the base stations using generalized eigenvector decomposition. Assuming full CSI feedback, $f_k$ is obtained as a solution to

$$R_{h_k} f_k = \lambda_k R_{g_k} f_k,$$

where $R_{h_k} = h_k h_k^T$ and $R_{g_k} = \alpha_k - g_k g_k^T + \frac{1}{\alpha_k} I_{N_t}$. The beamforming vector, $f_k$, chosen as the generalized eigenvector corresponding to the largest generalized eigenvalue in (2) was shown to approximately maximize the sum-rate. In the limited feedback case, the base station is assumed to have full knowledge of $\|h_k\|_2$ and $\|g_k\|_2$. The unit-norm channel directions, denoted by $\tilde{h}_k = h_k/\|h_k\|_2$ and $\tilde{g}_k = g_k/\|g_k\|_2$, are quantized using $B_d$ and $B_i$ bits, respectively. The quantized desired and interfering channel directions are denoted by $h_k$ and $g_k$, respectively. For a codebook $W = \{w_1, w_2, \ldots, w_B\}$, $\tilde{h}_k$ ($\tilde{g}_k$) are chosen according to

$$\tilde{h}_k = \arg \max_{w \in W} |\tilde{h}_k^* w|^2.$$

The beamforming vectors for limited feedback with the generalized eigenvector approach can be obtained at the base station using (2) by replacing $R_{h_k}$ and $R_{g_k}$ with $R_{h_k}$ and $R_{g_k}$, respectively [4]. The loss in sum-rate due to quantization, $\Delta R_s$, is upper-bounded by [4]

$$\Delta R_s \leq \sum_k \log_2 \left( \frac{|h_k^T f_{k,\text{opt}}|^2}{|h_k^T f_k|^2} \right) - \log_2 (|\tilde{h}_k^* h_k|)$$

$$+ \log_2 (1 + \rho_k \alpha_k |g_{k+1}|^2 (1 - |\tilde{g}_k^* g_{k+1}|^2)).$$

A limited feedback strategy was proposed in [4] to minimize the mean loss in sum-rate given in (4) for RVQ. The available feedback bits, $B$, were partitioned adaptively to quantize the desired and interfering channels using codebooks of sizes $B_d(\leq B)$ and $B_i = B - B_d$, respectively. It is to be noted that the strategy proposed in [4] used two separate codebooks for feeding back CSI of the two channels.

4. JOINT QUANTIZATION-BASED LIMITED FEEDBACK FOR GEBF

A fundamental result of vector quantization states that the distortion resulting from quantizing a vector may be smaller than that arising from quantizing each component separately, even when the entries are statistically independent [8]. Vector quantization has the ability to exploit linear and non-linear dependence among the coordinates and hence, has the extra freedom in choosing the multi-dimensional quantizer cell shapes or Voronoi regions [8]. In the multicell scenario, this result implies that for a given number of feedback bits, quantizing the desired and interfering channels jointly as a composite vector could yield a lower distortion (or, higher data rate) as compared to separate quantization for the same number of feedback bits.

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1 We drop the discrete-time index for sake of convenience.
The composite channel vector at the $k$th user is denoted by $[h_k; g_{k+1}]$. The idea is to generate codebooks, $W$, with codewords, $w_t(n = 1, \ldots, 2^B)$, such that $w_t(1 : N_t)$ and $w_t(N_t + 1 : 2N_t)$ are the quantized versions of $h_k$ and $g_{k+1}$, respectively. The selection criterion in (3) maximizes the terms $|h_k^* h_k|^2$ and $|g_{k+1}^* g_{k+1}|^2$ separately in (4), instead of jointly optimizing the right hand side of (4). In Section 4.1, we derive a selection criterion that minimizes the upper bound in (4), using RVQ. We develop a centroid design technique to design codebooks using the generalized Lloyd algorithm in Section 4.2.

4.1. Joint Quantization Using RVQ

In this section, we derive a selection criterion to choose codewords to minimize the mean loss in sum-rate, using RVQ. Each of the $2^B$ codebook vectors in the codebook is independently chosen from the isotropic distribution on the $N_t$ dimensional unit sphere [9]. We use RVQ for analytical tractability. We denote $w(1 : N_t) = w_h$ and $w(N_t + 1 : 2N_t) = w_g$. For RVQ, the expected value of the first term of (4) is zero [4]. The selection criterion for choosing a codeword for the $k$th user from a codebook $W$ is then derived from (4) as

$$\arg \max_{w \in W} \frac{|h_k^* w_h|^2}{1 + \rho \alpha k \|g_{k+1}\|^2(1 - |g_{k+1}^* g_{k+1}|^2)}.$$  \hspace{1cm} (5)

Note that in the case where the desired and interfering channels are quantized separately the above criterion boils down to choosing $h_k$ and $g_{k+1}$ that are respectively closest to $h_k$ and $g_{k+1}$ in direction. Using simulations, we show that jointly quantizing both the desired and interfering channels yields higher sum-rates than quantizing them separately, even for RVQ.

4.2. Joint Quantization Using GLA

In Section 4.1, RVQ is used for joint quantization. In this section, we hope to improve the performance gains obtained using joint quantization by generating codewords using the GLA. Though the selection criterion in (5) is developed for RVQ, in this section, we use it for obtaining codebooks using the GLA. Henceforth in this section, we drop the indices $k$ and $k + 1$ to simplify notation.

The codewords at the $m$th iteration of the GLA are given by $[\hat{h}_i^{(m)}; \hat{g}_i^{(m)}]$, $i \in \{1, 2, \ldots, 2^B\}$. We denote all the composite channel vector realizations that correspond to the $i$th codeword by $[\hat{h}_i^{(m)}; \hat{g}_i^{(m)}]$, $i \in \{1, 2, \ldots, 2^B\}$. $i$ represents the number of vectors that lie in the Voronoi region of the $i$th codeword. For the $k$th user, the contribution of the $i$th Voronoi region to the loss in sum-rate in (4) is

$$\Delta R_{k,i} = \frac{1}{N_t} \sum_{t=1}^{n_t} \left( \log_2(1 + \rho \alpha \|g_{i,t}^{(m)}\|^2(1 - |g_{i,t}^{(m)} h_{i,t}^{(m)}|^2)) \right) - \log_2(h_{i,t}^{(m)} h_{i,t}^{(m)}).$$

Assuming small quantization errors, $(1 - |h_{i,t}^{(m)} h_{i,t}^{(m)}|^2) \to 0$ and $(1 - |g_{i,t}^{(m)} g_{i,t}^{(m)}|^2) \to 0$. Since $\log(1 + x) \approx x$ for $x \approx 0$,

$$\Delta R_{k,i} \approx \frac{1}{N_t} \frac{\log_2(1 + \rho \alpha \|g_{i,t}^{(m)}\|^2)}{\log_2(1 + \rho \alpha \|g_{i,t}^{(m)}\|^2)} \left( \sum_{t=1}^{n_t} \rho \alpha \|g_{i,t}^{(m)}\|^2(1 - |g_{i,t}^{(m)} h_{i,t}^{(m)}|^2) \right) + \sum_{t=1}^{n_t} \rho \alpha \|g_{i,t}^{(m)}\|^2(1 - |g_{i,t}^{(m)} h_{i,t}^{(m)}|^2).$$

The expression in (6) is simplified by rearranging the terms

$$\Delta R_{k,i} \approx \frac{1}{N_t} \frac{\log_2(1 + \rho \alpha \|g_{i,t}^{(m)}\|^2)}{\log_2(1 + \rho \alpha \|g_{i,t}^{(m)}\|^2)} \left( \sum_{t=1}^{n_t} \rho \alpha \|g_{i,t}^{(m)}\|^2 + 1 \right) \left( \sum_{t=1}^{n_t} \rho \alpha \|g_{i,t}^{(m)}\|^2 - \rho \alpha \|g_{i,t}^{(m)}\|^2 \right)$$

Denoting $G_i = \frac{1}{n_t} \sum_{t=1}^{n_t} g_{i,t}^{(m)} g_{i,t}^{(m)^*}$ and $R_i = \frac{1}{n_t} \sum_{t=1}^{n_t} h_{i,t}^{(m)} h_{i,t}^{(m)^*}$, (7) is rewritten as

$$\Delta R_{k,i} \approx \frac{1}{N_t} \frac{\log_2(1 + \rho \alpha \|g_{i,t}^{(m)}\|^2)}{\log_2(1 + \rho \alpha \|g_{i,t}^{(m)}\|^2)} \left( \sum_{t=1}^{n_t} \rho \alpha \|g_{i,t}^{(m)}\|^2 + 1 \right) \left( \sum_{t=1}^{n_t} \rho \alpha \|g_{i,t}^{(m)}\|^2 - \rho \alpha \|g_{i,t}^{(m)}\|^2 \right)$$

The centroid of the Voronoi cell, i.e. the codeword at the $m$th iteration is given by $[\hat{h}_i^{(m)}; \hat{g}_i^{(m)}]$, where $h_{i}^{(m)}$ and $g_{i}^{(m)}$ are the eigenvectors corresponding to the largest eigenvalues of $R_i$ and $G_i$, respectively. Note that by using a sufficiently large number of sample points, $R_i$ and $G_i$ will not be rank-deficient.

It is known that the initialization of codewords is an important step to ensure the convergence of the GLA to a local optimum. Since we assume i.i.d. Rayleigh fading channels in this paper, we initialize the GLA by setting $[\hat{h}_i^{(0)}; \hat{g}_i^{(0)}]$, $i \in \{1, 2, \ldots, 2^B\}$ to be random i.i.d. isotropic vectors on an $N_t$ dimensional unit hypersphere.

5. SIMULATION RESULTS

In this section, we assume that all the users in the multicell system have the same received SNR of the desired and interfering signals, for simplicity of simulations. In Fig. 2, we compare the sum-rates obtained using the joint quantization techniques in Sections 4.1 and 4.2 with separate quantization approaches, for $B = 6$, $\rho = 10 \text{ dB}$, $N_t = 2$ and the number of cells, $K = 2$. We also plot the sum-rates obtained using multicell dirty paper coding (DPC) [2] and generalized eigenvector beamforming with full CSI, as a reference. For the separate quantization approaches, we use the feedback-bit allocation algorithm in [4] as well as two separate Grassmann
In this paper, we considered limited feedback for multicell MISO systems using cooperative generalized eigenvector beamforming. We proposed jointly quantizing the desired and interfering channels as a composite vector to yield higher sum-rates than the separate quantization approach in literature. We first consider joint quantization using RVQ and derive a new selection criterion to minimize the loss in sum-rate of a multicell system. We then use the GLA to generate codebooks by developing a codeword design technique. Using simulations, we showed that joint quantization of the desired and interfering channels yields sum-rates that are not only higher than the separate codebook approach, but also very close to the full-CSI case with sufficient number of feedback bits. This is a strong motivation for joint quantization of the desired and interfering channels.

6. CONCLUSION

In this paper, we considered limited feedback for multicell MISO systems using cooperative generalized eigenvector beamforming. We proposed jointly quantizing the desired and interfering channels as a composite vector to yield higher sum-rates than the separate quantization approach in literature. We first consider joint quantization using RVQ and derive a new selection criterion to minimize the loss in sum-rate of a multicell system. We then use the GLA to generate codebooks by developing a codeword design technique. Using simulations, we showed that joint quantization of the desired and interfering channels yields sum-rates that are not only higher than the separate codebook approach, but also very close to the full-CSI case with sufficient number of feedback bits. This is a strong motivation for joint quantization of the desired and interfering channels.

7. REFERENCES


Fig. 2. Mean sum-rate as a function of $\alpha$ for different quantization approaches for $\rho = 10$ dB, $N_t = K = 2$ and $B = 6$.

Fig. 3. Mean sum-rate as a function of $\alpha$ for joint quantization with RVQ and GLA for $\rho = 10$ dB, $N_t = K = 2$ and $B = 4, 8, 12$. 