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Labeling-based Zero-forcing Beamforming for LTE MU-MIMO*

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Abstract:A smart MU-MIMO operation method in TD-LTE system is proposed,which combines the merits of both BF(Beamforming) and CL-MIMO(Closed Loop MIMO). Once obtaining the estimated channel information when receiving UL-SRS(Uplink Sounding Reference Signal) from UE,the eNB will quantify them as labels using pre-determined codebook in physical layer L1. Then L1 conveys those chosen labels to L2 in which scheduler will use those labels for MU scheduling. It will well solve the two problems of zero-forcing UEs pairing and the cross-layer resource allocation procedure between L1 and L2. And finally,L1 will generate the BF precoding matrix without heavy computation. This paper proposes a general framework for the system implementation with anticipated sub-optimal performance. To reach the objectives,new design criteria on codebook and quick algorithm for generation on precoding matrix are proposed.

Key words:MU-MIMO;beamforming;zero-forcing;codebook design criteria

用于 LTE MU-MIMO 的标签迫零波束成形技术

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摘 要:提出了一种聪明的 TD-LTE MIMO 操作模式,它结合了波束成形技术和闭环反馈 MIMO 的优点。当 eNB 获得 UE 上行 SRS 参考信号的信道信息,L1 进行基于码本的信道估计量化和标签化。L1 将标签上传到 L2,L2 基于标签进行多用户调度,这样较好地解决了基于迫零的 UE 配对和 L1/L2 间跨层资源分配这两个问题。L1 无需更多计算便可生成波束成形的预编码矩阵。同时,提出了在可接受的次优性能下一种易实现的一般性框架。为了达到目标,给出了新的码本设计标准和快速预编码矩阵的生成算法。

关键词:MU-MIMO;波束成形;迫零;码本设计标准
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1 Introduction

For downlink broadcast channel,the best solution is to use the DPC(Dirty Paper Coding) algorithm to minimize the inter-stream interference(ISI) or the mutual user interference(MUI) to reach the maximum sum channel capacity. However,the DPC is much more complex and needs much prior-information of users at eNB[1-3]. It is a normal way to use Zero-Forcing(ZF) technique by choosing multiple streams or users transmitted simultaneously but with good orthogonality of spatial channel. When there are many users in the cell, the opportunity to find the final ZF users is largely in-

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creased and it could reach the theoretical sum capacity.

From the perspectives of system realization of MU-MIMO, there are three key issues to be solved: 1) to maximize the system sum rate of MU-MIMO; 2) to maximize the sum rate of selected paring users in the MU-MIMO; 3) to simplify the cross-layer resource allocation procedure between L1 and L2. For normal operation, L1 performs channel estimation based on UL-SRS, and L2 makes the scheduling decisions according to scheduling algorithms, for example, proportional fair (PF), then sends DL grant back to L1, eventually L1 calculates final BF weight using ZF algorithm for paired users chosen by the user pairing algorithm. System performance is affected by the eNB computation capability, delay and accuracy of pairing UEs' selection.

For TDD, we take advantage of channel reciprocity and using UL-SRS for channel estimation. Here we design a sub-optimization algorithm and try to deal with the three problems at the same time. Instead of getting precise channel estimation from UL-SRS, we quantize the estimated channel and label them in L1. With labelling those estimated channel, we would: 1) have larger label quantization space with fine granularity; 2) do sub-band based labeling by having full band UL-SRS information.

As far as the CL-MIMO is considered, CL-MIMO can use the codewords as precoding matrix directly for SU-MIMO (Single User MIMO), which needs less calculation. But for MU-MIMO, multiple user pairing and ZF are still required for avoiding ISI/MUI. Also the codebook space is limited by the feedback channel bandwidth. Compared with codebook-based CL-MIMO, label-based beamforming has some improvements. 1) Label design is very flexible to different application scenarios. It does not only include channel spatial information, but also attaches the correlation information between the estimated channel and the codeword; 2) the term 'label' is borrowed from MPLS (Multiple Protocol Label Switch), a very successful technique in high speed IP network. In MPLS, the PE routers classify the inflow traffic and mark the labels for different purposes: forwarding, VPN, QoS or traffic engineering, and etc; P routers perform the quick routing and forwarding based on the labels and do not process any in-depth packet inspection. Same concept is applied for the LTE cross layer resource allocation in this paper, the L1 classifies the UE's CSI and marks the labels, L2 does the UE pairing and scheduling based on the labels and there is no need for L1 to recalculate BF weights after UE pairing. In fact in traditional solution, the CSI information has not been delivered to L2 fully. And the L1 does the calculation twice, CSI estimation and ZF operation. 3) The framework solution can be easily extended to CoMP (Coordinated MultiPoint) operation. Meanwhile, the CoMP eNBs can get more accuracy CSI by measuring UE UL-SRS directly.

To exploit the benefits of ZF, we need to design a new cookbook to provide much more orthogonal codewords. The codewords should be finely partition the H complex manifold. The labeling method should provide the correlation information between the codewords. For the mapping between codeword and transmission channel, it is hard to guarantee the orthogonality between different UEs, we need a way to select pairing UEs with quasiorthogonal relationship and generate the orthogonal precoding matrix easily with proper ranks.

Labeling-based BF combines the merits of both traditional BF and CL-MIMO. There are tons of papers to provide solutions for traditional BF and CL-MIMO respectively. This paper does not try to improve them, instead, it provides the third way to reduce the calculation needed and hence reduce the eNB hardware cost for MU-MIMO operation. The similar ideas have not been found to the best of our knowledge in previous studies.

We describe our solutions in the sections below. In the second section, channel model is provided. The third section addresses a new codebook design criteria and labeling method. The next section focuses on the MU-MIMO in one cell with the proposed labeling framework. Finally, the conclusion is given.

2 Channel Model

Here we prefer to use the model nomenclature from Reference [1] for general purpose.

We typically consider a subset of a cellular system consisting of M BSs and K UEs, N_{bs} and N_{ue} denote the number of antennas per BS and per UE, respectively, and where $N_{\mathrm{BS}}=MN_{\mathrm{bs}}$ and $N_{\mathrm{UE}}=KN_{\mathrm{ue}}$ denote the overall number of antennas at BS and UE side, respectively.

$$\tilde{x}=G^{\mathrm{H}}y=\begin{bmatrix} G_1^{\mathrm{H}} & & 0 \\ & \ddots & \\ 0 & & G_K^{\mathrm{H}} \end{bmatrix}(\boldsymbol{H}^{\mathrm{H}}Wd(x)+n)$$

where $x\in C^{[N_{\mathrm{UE}}*1]}$ are the symbols to be transmitted to the UEs, and $d(\cdot)$ can be any arbitrary manipulation of these symbols performed by the BSs. $W\in C^{[N_{\mathrm{BS}}*N_{\mathrm{UE}}]}$ is a precoding matrix applied at the BS side. The transmit covariance is now given as $\Phi_{ss}=E\{Wd(x)(d(x))^{\mathrm{H}}W^{\mathrm{H}}\}$ which is typically subject to either per-BS or per-antenna power constraint (Here we discuss the per-antenna power constraint case). $G\in C^{[N_{\mathrm{UE}}*N_{\mathrm{UE}}]}$ is a matrix containing the UE- side receiving filters, which is block-diagonal. $n\in C^{[N_{\mathrm{UE}}*1]}$ is the thermal noise and background interference present at the receiving antennas of the UEs, which we assume zero-mean Gaussian with covariance $\Phi_{nn}=E\{nn^{\mathrm{H}}\}=\sigma^2 I$. Each UE finally obtains estimates $\tilde{x}\in C^{[N_{\mathrm{UE}}*1]}$ of the originally transmitted symbols x. We also denote as H^m, H_k, H_k^m the parts of the channel matrix $H\in C^{[N_{\mathrm{BS}}*N_{\mathrm{UE}}]}$ connected to BS m, UE k, or the link from BS m to UE k, respectively.

Let us observe one UE k which is served by BS $m=k$. we denote as K_m the set of all UEs served by BS m simultaneously on the same resource, which is obviously limited to the number of BS transmit antennas, e. g. $|K_m|\leqslant N_{\mathrm{bs}}$. One stream u of received signals of our observed UE k can be expressed as

$$y_{k,u}=\underbrace{H_{k,u}^{\mathrm{H}}W_{k,u}x_{k,u}}_{H_{k,u}}+\underbrace{\sum_{v\neq u}H_{k,u}^{\mathrm{H}}W_{k,v}x_{k,v}}_{\text{inter stream intrf.}}+\underbrace{\sum_{j\in\{K_m\backslash k\}}H_{k,u}^{\mathrm{H}}W_jx_j+n_{k,u}}_{\text{intra-cellintrf. and noise }\xi_k}\qquad(1)$$

Here we only think about the SINR attransmitted side since the precoding is primarily affected by the transmit correlation.

$$SINR_{k,u}=\frac{W_{k,u}^{\mathrm{H}}H_{k,u}H_{k,u}^{\mathrm{H}}W_{k,u}}{W_{k,u}^{\mathrm{H}}Z_{k,u}W_{k,u}}$$

Where $Z_{k,u}$ is the covariance matrix of the streams received by UE k (except stream u) and the interfering signals and noise aggregated in ξ_k, i. e. $Z_{k,u}=\sum_{v\neq u}H_{k,v}H_{k,v}^{\mathrm{H}}+E\{(\xi_k)(\xi_k)^{\mathrm{H}}\}$.

3 Codebook Design and Labeling

3.1 Codebook Design

In 3GPP 36. 213, there is a definition for codebook based on Discrete Fourier Transform (DFT) for 8-antenna system. But for 8-dimensional complex manifold, the DFT-based codebook has not partitioned the complex manifold evenly, it has not pursued the good cross orthogonal between the codewords (in 128 codewords, only 4 codewords are mutual orthogonal), and it has not depicted the relationship among the codewords by codebook indices.

The codebook design is the key for the solution. We can either modify the 3GPP codebook or design a new codebook by using the Grassmannian line-packing method[4] with some extra restrictions.

The modification of the 3GPP existing codebookwill have quick solution even though the partition of the H manifold is not good enough. We can expand the codebook to full rank of H manifold by Gram-Schmidt process first, and then divide the codewords into ordered basis groups, finally use the labeling method described in 3. 2 to re-label them.

Alternatively we use the Grassmannian line-packing method suggested by Reference [4] which provides the method to partition the H manifold into various subspace. We need modify it for our solution by full rank partition and all basis vectors being in ordered.

We will focus on the design of a Grassmannian quantization codebook, $C=\{C_1,C_2,\cdots,C_N\}$, in which the matrices $C_i\in C^{[8\times8]}$ represent an ordered basis of Grassmannian manifold, each column $C_{i,p}$ is a $C^{[8\times1]}$ orthonormal complex vector. We will denote the corresponding Grassmannian manifold by $G_{8,8}$. We have N group ordered bases; each basis has 8 orthonormal complex vectors. And we have $8\times N$ codewords in codebook. Suppose the C_j is a rotational transformation of C_i, for ordered basis, we have $\mathrm{Re}(C_{i,p}*C_{j,p}^{\mathrm{H}})=\mathrm{Re}(C_{i,q}*C_{j,q}^{\mathrm{H}})$, $i\neq j,p\neq q$. We try to find a codebook $C=\{C_1, C_2,\cdots,C_N\}$ that solves

$$\max_{\{C_i\},C_i\in G_{8,8}}\min_{i\neq j}|\gamma(C_{i,p},C_{j,q})|;\ p,q=1,,8$$

$$\gamma(C_{i,p},C_{j,q})=\mathrm{Re}(C_{i,p}*C_{j,q}^{\mathrm{H}});\ p,q=1,,8$$

$\gamma(C_{i,p},C_{j,q})$ is the complex correlation between two codewords.

3.2 Labeling Method

Assume we have size $8 \times N$ codebook $\{C_1, C_2, \cdots, C_N\}$. In comparison with the traditional codebook designs, we not only provide codewords to finely partition the H manifold, but also try to build embedded relationship between the codewords. We know codewords in same basis group are orthogonal, i. e. $\gamma(C_{i,p}, C_{i,q}) = 0$; $p, q = 1, , 8$. We calculate all cross correlation coefficient for inter basis groups $\gamma(C_{i,p}, C_{j,p})$; $p = 1, , 8, i \neq j$. We can get a correlation matrix $R = [\gamma_{ij}]_{N\times N}$, with the value of γ_{ij}, we try to build a circular sequence for basis groups, in this sequence, each group has high γ with its adjacent groups. The γ will be decreased with the distance of two groups increased. We denote the distance $L(C_i, C_j)$, $i \neq j$ of two groups as

$$L(C_i, C_j) = \begin{cases} |[i]-[j]|, 1 \leqslant |[i]-[j]| \leqslant N/2 \\ N - |[i]-[j]|,\ N/2 < |[i]-[j]| < N \end{cases}$$

i, j are the group number of the ordered basis, $[i]$ is the modulo group of N. The distance is the value of two groups' modulo minus.

With total $P = \{N!$ permutation of N group bases$\}$, we try to find the sequence meets

$$\arg\min_P \{\sum_{i\in N} (\gamma_{[i][i+n/2]} - \gamma_{[i][i-1]} - \gamma_{[i][i+1]})\}$$

Then we will get a circular list, which maps the group number of the ordered basis C_i, the first subscript of the codeword, and make sure the second subscripts of different groups are one to one mapping according to ordered bases.

Furthermore, we can classify the ordered basis group's neighbors into different groups based on their correlation. In an acceptable range, one codeword in one basis group can be replaced by the corresponding codeword in the adjacent basis group without injecting much interference. Without loss of generality, we focus on $C_{1,1}$, according to the value of γ, we can divide other $C_{i,p}$ into different groups, and use $C_{i,1}$ as the representation of the corresponding basis group and calculate γ_{1i}:

Group 1, G1, $i = 1, p \neq 1$, fully orthogonal

Group 2, G2, for $\theta_1 < \gamma_{1i}$, $i \neq 1$, pseudo orthogonal

Group 3, G3, for $\theta_2 < \gamma_{1i} \leqslant \theta_1$, $\theta_2 \leqslant \theta_1$, $i \neq 1$, middle orthogonal

Group 4, G4 for $\gamma_{1i} < \theta_2$, others

The G_i groups depict the level of interference among each other if UEs are in different G_i, we can use this information to decide pairing number to get the acceptable spatial multiplex throughput.

When eNB measures UL-SRS of UE i and estimates the UE i's channel $H_i^{\mathrm{H}} \in C^{[N_{\mathrm{ue}} * N_{\mathrm{bs}}]}$, for one stream, $N_{\mathrm{ue}} = 1$, and chooses the label as

$$C_{i,k} = \arg\max_{C_{i,k}\in\mathbb{C}} \mathrm{Re}(H_i^{\mathrm{H}} C_{i,k});$$

for two steams, UE i has two labels.

4 Labeling-based ZF BF Algorithm

For spatial multiplex operation, we try to transmit multiple streams at the same RB position. The simplest way is choosing multiple streams from single UE or multiple UEs which happens to have orthogonal or quasiorthogonal channel paths.

In realization, we try to use ZF principal to pair UEs and try to make the formula (1) only remain the most left term, others terms are canceled by choosing orthogonal BF weights.

We use ZF to minimize the inter stream interference and inter user interference. Let 1) $W_{k,u} = H_{k,u}$; 2) select the other stream of UE k, named stream v if exist, $H_{k,v} \neq H_{k,u}$, and $H_{k,v}^{H} W_{k,u} = 0$; We always assume the orthogonality between the streams for one UE due to the eigenvectors decomposition. 3) For intra cell interference, there is no orthogonality guarantee between the UEs, however, we can choose UE_j with low correlation to UE_k. The information can be obtained from the UE's labels. After UEs being paired by the L2 scheduling, L1 can project the paired UE_j's W_j to the orthogonal direction of UE_k, as $\widetilde{W}_j$, which is in the same ordered basis group of UE_k. UE_j uses the weigh $\widetilde{W}_j$, and $(H_k)^{\mathrm{H}} \widetilde{W}_j = 0$, i. e. $\xi_k = \sigma^2$; Then the $SINR_{k,u}$ of this stream will be degenerated to SNR $\rho_{k,u}$. We call this rule is the ZF principle. At the eNB, we generate a precoding matrix $W \in C^{[N_{\mathrm{bs}} * d]}$ with orthonormal columns.

When pairing those users on the same RB position, we can determine stream number d according to available labels. E. g. , if UE1's label is $C_{1,1}$ and is chosen for scheduling according to the PF scheduling, we seek for other UEs to pair. If other UEs' CSI belongs to G1, we can pair up to maximum $d = 4$ users or streams. If other UEs' CSI belongs to G2 or G1, we can choose $d = 3$. If other UEs belong to G3 or G2, we can choose $d = 2$. If we cannot find the proper UEs, we give up pairing chance otherwise it will cause large inter-stream or inter-UE interference. In fact, threshold θ_i and maximal paired stream number d are configurable parameters on requirement.

The labeling-based zero-forcing beamforming algorithm is:

a) Select users with high SNRs into MU candidate set;

b) On any RB, according to the proportional fair algorithm, choose the highest priority UE k in the scheduling queue. Let $W_k = H_k = C_{i,p}$;

c) According to i in the $C_{i,p}$, find out other UEs belong to which G groups, based on available labels of other UEs, we can determine the pairing $d-1$ streams on the same RB;

d) Repeat step-c until all d layers/users are chosen, one UE can have maximum two layers chosen if the UE's labels meet the ZF principal and SNR threshold.

After pairing, L2 send grant to L1, then L1 check the pairing UEs labels, which may be $C_{j,q}, q \neq p, i \neq j$, L1 uses the weight $\widetilde{W}_j = C_{i,q}, q \neq p$ as the final beamforming weight vector column in the precoding matrix.

In the eNB realization, the precoding matrix is restricted by per-antenna power limit of eNB. It may introduce new ISI/MUI by adjustment of precoding matrix.

There are two typical operations to do the BF weights normalization in system realization to avoid overflowing the per-antenna power limit. One is to do per-element based normalization, i. e.

$$(W_k)_{i,j} = (W_k)_{i,j} / |(W_k)_{i,j}|.$$

The other is to do max-element based normalization, i. e.

$$(W_k)_j = (W_k)_j / |\max (W_k)_j|.$$

However, the former operation is non-linear transformation and will cause new ISI/MUI. The latter can cause power loss for eNB. For labeling-based ZF BF solution, ISI and MUI are easily avoided due to those orthogonal normalized codebooks. If we design good codebooks and keep certain size of these codebooks, the combination of each ordered basis as the precoding matrix is anticipated and can be calculated offline and adjusted beforehand. This keeps simple for implementation.

5 Conclusion

In this paper, a simple labeling-based beamforming for MU-MIMO in TD-LTE system has been proposed. It quantizes the UL-SRS per UE as labels. And, the labels are relayed to L2. In L2, it performes MU pairing, RB allocation etc. then sends grant to L1. In L1, it gets final pre-coding weights according to granted label information. To differentiate from traditional ZF-based beamforming operation, it does not need the complex calculation for UE pairing and precoding matrix generation any more, which will largely reduce computational complexities of eNB. This framework is easy to expand to FDD-LTE system if we label the feedback PMI also from users in FDD mode.

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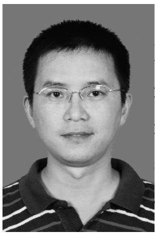
Biography:



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