LTE-Advanced Multi-User MIMO: Improved Feedback and Precoding Design

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***Abstract*—This paper considers feedback and precoding design for multi-user MIMO in long term evolution (LTE) and LTE-Advanced systems. We show that LTE precoders are characterized by a diversity loss, mainly attributed to their characteristic of equal gain transmission (EGT). We therefore propose a precoding design based on marginal increase of feedback and show that the performance of multi-user MIMO comes quite close to the lower bound. We claim that the proposed codebook structure is not only restricted to the framework of LTE and LTE-Advanced, but also applicable as a fundamental design guidance for the ongoing standardizations of modern wireless systems.**

I. Introduction

In the pursuit of ever-increasing demands of higher data rates, wireless communication has been revolutionized in the last decade by exploiting the spatial dimension on top of the classical dimensions of time and frequency. This new additional degree of freedom in the form of multiple antennas at the transmitter and receiver (MIMO) promises improved reliability (transmit and receive diversity), higher spectral efficiency (stream multiplexing) and spatial separation of users (user multiplexing). User multiplexing or multi-user MIMO is particularly beneficial in the downlink of multi-user cellular systems for serving multiple users on the same time-frequency resources. The consequential higher throughput is particularly envisioned for the downlink of future cellular standards as third generation partnership project long term evolution (3GPP LTE) and LTE-Advanced [1], which are targeting 100Mbps in high-mobility applications and 1Gbps for low-mobility applications such as nomadic / local wireless access.

Multi-user MIMO promises a significant increase in the spectral efficiency as compared to single-user MIMO, however these promised gains are highly dependent on the availability of channel state information at the transmitter (CSIT). Full acquisition of CSIT in a practical system, particularly in a frequency division duplex (FDD) system, is far from realizable. The complexity associated with the feedback overhead coupled with the low rate feedback channels are the major impediments in CSIT acquisition. Future wireless systems therefore consider multi-user MIMO strategies based on limited or quantized CSIT.

On the design of feedback, there is stark contrast between the theoretically established results and current standards. Theory has established that the amount of CSIT feedback in a downlink system needs to grow in proportion to the SNR [2] and otherwise the degrees of freedom are lost. However to avoid the burden of feedback and due to complexity constraints, the modern wireless systems have been restricted to fixed rate feedback schemes. With such premises, LTE and LTE-Advanced have focused on the structured precoder codebook based approach [1] by using a small number of feedback bits. This fixed low-level quantization of LTE codebook eclipses most of the benefits of multi-user MIMO and raises questions about the feasibility of this mode of transmission [3, page 244].

In an effort of bridging the gap between the theory and practice, this paper investigates the structure of LTE codebook by analyzing the pairwise error probability (PEP) expressions. The analysis shows that LTE precoders suffer from the loss of diversity when being employed in multi-user MIMO transmission mode but no such loss is observed in single-user MIMO mode. Based on this analysis, we propose a new codebook design and show that with a nominal increase in the feedback, the performance of multi-user MIMO improves quite close to the lower bound (single-user MIMO). To verify the proposed codebook design, we consider widely studied Gaussian random codebooks [2], for comparison. Note that though the overall discussion in this paper has generally been on LTE and LTE-Advanced framework, the proposed feedback and precoding design can serve as a guideline for multi-user MIMO modes in any other modern wireless system which employs limited feedback schemes for CSIT acquisition.

The paper is organized as follows. In Section II, we give an overview of LTE and LTE-Advanced and define the system model. Section III looks at the coded PEP analysis of the currently standardized LTE and LTE-Advanced codebooks both for single-user and multi-user MIMO transmission; while Section IV focuses on the proposed feedback and codebook design. Section V encompasses the simulation results, which are followed by the conclusions.

II. System Model

In this paper, we focus on the baseline configuration where an eNodeB is equipped with two antennas and transmit downlink to multiple user equipments (UEs) with single antennas. Like other ongoing standardizations of wireless communication systems such as IEEE 802.16m (WiMAX) and IEEE 802.11n (Wireless LAN), LTE is also based on OFDMA (Orthogonal Frequency Division Multiple Access) combined with bit interleaved coded modulation (BICM).

During the transmission for UE-1, the code sequence $\underline{\mathbf{c}}_1$ is interleaved by π_1 and is then mapped onto the signal sequence

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$\underline{\mathbf{x}}_1$. The bit interleaver for UE-1 can be modeled as $\pi_1 : k^{'} \rightarrow (k,i)$ where $k^{'}$ denotes the original ordering of the coded bits $c_{k'}$, k denotes the resource element (RE - LTE acronym for subcarrier) of the symbol $x_{1,k}$ and i indicates the position of the bit $c_{k'}$ in symbol $x_{1,k}$. Note that $x_{1,k} \in \chi_1$ is a symbol of $\underline{\mathbf{x}}_1$ where $\chi_1 \subseteq \mathcal{C}$. Each RE corresponds to a symbol from a constellation map χ_1 for UE-1 and χ_2 for UE-2. Selection of normal or extended cyclic prefix for each OFDM symbol converts downlink frequency-selective channels into parallel flat fading channels. Cascading IFFT at the eNodeB and FFT at the UE with the cyclic prefix extension, the transmission at the k-th RE for UE-1 can be expressed as

$$y_{1,k} = \mathbf{h}^{\dagger}_{1,k}\mathbf{p}_{1,k}x_{1,k} + \mathbf{h}^{\dagger}_{1,k}\mathbf{p}_{2,k}x_{2,k} + z_{1,k} \tag{1}$$

where $y_{1,k}$ is the received symbol at UE-1 and $z_{1,k}$ is zero mean circularly symmetric complex white Gaussian noise of variance N_0. The complex symbols $x_{1,k}$ and $x_{2,k}$ are assumed to be independent and of variances σ_1^2 and σ_2^2 respectively. $\mathbf{h}^{\dagger}_{n,k} \in \mathbb{C}^{1\times 2}$ symbolizes the spatially uncorrelated flat Rayleigh fading MISO channel from the eNodeB to the n-th UE $(n = 1, 2)$ at the k-th RE where $\mathbb{C}^{1\times 2}$ denotes the 2-dimensional complex space. $\mathbf{p}_{n,k}$ denotes the precoding vector for the n-th UE at the k-th RE and is given by

$$\mathbf{p} = \left\{ \frac{1}{\sqrt{4}}\begin{bmatrix}1\\1\end{bmatrix}, \frac{1}{\sqrt{4}}\begin{bmatrix}1\\-1\end{bmatrix}, \frac{1}{\sqrt{4}}\begin{bmatrix}1\\j\end{bmatrix}, \frac{1}{\sqrt{4}}\begin{bmatrix}1\\-j\end{bmatrix} \right\} \tag{2}$$

III. Pairwise Error Probability Analysis

A. Single-user MIMO

We first consider the case of single-user MIMO. The received signal is written as

$$y_{1,k} = \mathbf{h}^{\dagger}_{1,k}\mathbf{p}_{1,k}x_{1,k} + z_{1,k}$$

Channel to UE-1 from eNodeB is $\mathbf{h}^{\dagger}_{1,k} = \begin{bmatrix} h^*_{11,k} & h^*_{21,k}\end{bmatrix}$. For precoding, we consider the matched filter (MF) based precoder with the restriction of EGT, i.e. the precoding vector is given as $\mathbf{p}_{1,k} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\ \frac{h_{21,k}h^*_{11,k}}{|h_{21,k}||h_{11,k}|}\end{bmatrix}$ where the second entry is the angle between two channel coefficients. The PEP analysis of this precoder would serve as a lower bound to that of LTE precoders (2) where in addition to EGT, lower angular resolution (four rotation angles) is also imposed, i.e. the second entry of the precoding vector is quantized to $1, -1, j$ or $-j$. The received signal is given by

$$y_{1,k} = \frac{1}{\sqrt{2}}h^*_{11,k}\left(1 + \frac{|h_{21,k}|}{|h_{11,k}|}\right)x_{1,k} + z_{1,k}$$

Now if we use $\frac{h_{11,k}}{|h_{11,k}|}$ as the receive filter, then the received signal is given as

$$\frac{h_{11,k}}{|h_{11,k}|}y_{1,k} = \frac{1}{\sqrt{2}}\left(|h_{11,k}| + |h_{21,k}|\right)x_{1,k} + \frac{h_{11,k}}{|h_{11,k}|}z_{1,k} \tag{3}$$

For the simplicity of notations, we use $y_{1,k} = \frac{h_{11,k}}{|h_{11,k}|}y_{1,k}$. The effective channel seen by the desired stream $x_{1,k}$ is given as $\frac{1}{\sqrt{2}}\left(|h_{11,k}| + |h_{21,k}|\right)$. The max Log MAP bit metric is given as

$$\lambda_1^i\left(y_{1,k}, c_{k'}\right) \approx \min_{x_1 \in \chi^i_{1,c_{k'}}} \frac{1}{N_0}\left|y_{1,k} - \frac{1}{\sqrt{2}}\left(|h_{11,k}|+|h_{21,k}|\right)x_1\right|^2$$

Conditional PEP i.e $P\left(\mathbf{c}_1 \rightarrow \hat{\mathbf{c}}_1|\mathbf{h}_1\right) = P^{\hat{\mathbf{c}}_1}_{\mathbf{c}_1}$ is given as

$$P^{\hat{\mathbf{c}}_1}_{\mathbf{c}_1} = P\left(\sum_k \min_{x_1 \in \chi^i_{1,c^{'}_k}} \frac{1}{N_0}\left|y_{1,k} - \frac{1}{\sqrt{2}}\left(|h_{11,k}|+|h_{21,k}|\right)x_1\right|^2 \geq \sum_k \min_{x_1 \in \chi^i_{1,\hat{c}^{'}_k}} \frac{1}{N_0}\left|y_{1,k} - \frac{1}{\sqrt{2}}\left(|h_{11,k}|+|h_{21,k}|\right)x_1\right|^2\right) \tag{4}$$

where $\mathbf{c}_1$ is the transmitted and $\hat{\mathbf{c}}_1$ is the error codeword. For the worst case scenario once $d\left(\mathbf{c}_1 - \hat{\mathbf{c}}_1\right) = d_{free}$ (free distance of the code), the inequality in (4) shares the same terms on all but d_{free} summation points and the summations can be simplified to only d_{free} terms for which $\hat{c}_{k'} = \bar{c}_{k'}$ where $\bar{(.)}$ indicates the binary complement. Let's denote

$$\tilde{x}_{1,k} = \arg\min_{x_1 \in \chi^i_{1,c_{k'}}} \frac{1}{N_0}\left|y_{1,k} - \frac{1}{\sqrt{2}}\left(|h_{11,k}| + |h_{21,k}|\right)x_1\right|^2$$

$$\hat{x}_{1,k} = \arg\min_{x_1 \in \chi^i_{1,\bar{c}_{k'}}} \frac{1}{N_0}\left|y_{1,k} - \frac{1}{\sqrt{2}}\left(|h_{11,k}| + |h_{21,k}|\right)x_1\right|^2$$

Note that

$$\left|y_{1,k} - \frac{1}{\sqrt{2}}\left(|h_{11,k}|+|h_{21,k}|\right)x_{1,k}\right|^2 \geq \left|y_{1,k} - \frac{1}{\sqrt{2}}\left(|h_{11,k}|+|h_{21,k}|\right)\tilde{x}_{1,k}\right|^2$$

We focus on equal energy alphabets and consider the case of slow fading channel, i.e. the channel remains constant for the duration of one codeword. We rewrite (4) in vector formulation i.e.

$$\sum_{k,d_{free}}\left|y_k - \frac{1}{\sqrt{2}}\left(|h_{11}|+|h_{21}|\right)x_{1,k}\right|^2 = \left\|\mathbf{y} - \frac{1}{\sqrt{2}}\left(|h_{11}|+|h_{21}|\right)\mathbf{x}_1\right\|^2$$

So conditional PEP is given as

$$\begin{aligned}
P^{\hat{\mathbf{c}}_1}_{\mathbf{c}_1} &\leq P\left(\left\|\mathbf{y} - \frac{1}{\sqrt{2}}\left(|h_{11}|+|h_{21}|\right)\mathbf{x}_1\right\|^2 \geq \left\|\mathbf{y} - \frac{1}{\sqrt{2}}\left(|h_{11}|+|h_{21}|\right)\hat{\mathbf{x}}_1\right\|^2\right) \\
&= P\left(\Re\left(\left(\frac{1}{\sqrt{2}}\left(|h_{11}| + |h_{21}|\right)\mathbf{x} + \mathbf{z}\right)^{\dagger}\left(\mathbf{x}_1 - \hat{\mathbf{x}}_1\right)\right) \leq 0\right) \\
&= P\left(\frac{1}{\sqrt{2}}\left(|h_{11}|+|h_{21}|\right)\left(\|\mathbf{x}_1\|^2 - \Re\left(\mathbf{x}_1^{\dagger}\hat{\mathbf{x}}_1\right)\right) + \Re\left(\mathbf{z}^{\dagger}\left(\mathbf{x}_1 - \hat{\mathbf{x}}_1\right)\right) \leq 0\right)
\end{aligned} \tag{5}$$

Using $\|\mathbf{x}_1 - \hat{\mathbf{x}}_1\|^2 = \|\mathbf{x}_1\|^2 + \|\hat{\mathbf{x}}_1\|^2 - 2\Re\left(\hat{\mathbf{x}}_1\mathbf{x}\right)$ we get

$$\begin{aligned}
P^{\hat{\mathbf{c}}_1}_{\mathbf{c}_1} \leq\; & P\left(\left(|h_{11}|+|h_{21}|\right)\left(\frac{3}{2\sqrt{2}}\|\mathbf{x}_1\|^2 - \frac{1}{2\sqrt{2}}\|\mathbf{x}_1 - \hat{\mathbf{x}}_1\|^2 + \frac{1}{2\sqrt{2}}\|\hat{\mathbf{x}}_1\|^2\right)\right. \\
&\left. + \Re\left(\mathbf{z}^{\dagger}\left(\mathbf{x}_1 - \hat{\mathbf{x}}_1\right)\right) \leq 0\right) \\
=\; & P\left(\kappa\left(|h_{11}| + |h_{21}|\right) + z^{'} \leq 0\right)
\end{aligned}$$

where $\kappa = \frac{3}{2\sqrt{2}}\|\mathbf{x}_1\|^2 - \frac{1}{2\sqrt{2}}\|\mathbf{x}_1 - \hat{\mathbf{x}}_1\|^2 + \frac{1}{2\sqrt{2}}\|\hat{\mathbf{x}}_1\|^2$. $z^{'} = \Re\left(\mathbf{z}^{\dagger}\left(\mathbf{x}_1 - \hat{\mathbf{x}}_1\right)\right)$ is circularly symmetric complex while

Gaussian noise of variance $\frac{N_0}{2}\|\mathbf{x}-\hat{\mathbf{x}}_1\|^2$. So the PEP is upperbounded as

$$P(\mathbf{c}_1 \to \hat{\mathbf{c}}_1|\mathbf{h}_1) = P\left(\kappa\left(|h_{11}|+|h_{21}|\right)+z^{'} \leq 0\right) \quad (6)$$

As per ours notations, the decision variable γ as per (5) and (13) in [4] is given as

$$\gamma = \kappa\left(|h_{11}|+|h_{21}|\right)+z^{'} \quad (7)$$

So the probability of error which is given as $P(\gamma \leq 0)$ is given as

$$P_e = \frac{1}{2}\left\{1-\frac{\sqrt{\rho_{11}(\rho_{11}+2\kappa)}+\sqrt{\rho_{21}(\rho_{21}+2\kappa)}}{\rho_{11}+\rho_{21}+2\kappa}\right\} \quad (8)$$

where $\rho_{ij} = \mathbb{E}\left(|h_{ij}|^2\right)/N_0$ is the SNR at the individual branch and κ is a constant that will depend on the constellation. (8) shows the full diversity order of 2, a result earlier derived for EGT in single-user MIMO systems in [5] using the approach of metrics of diversity order.

B. Multi-user MIMO

We now focus on the PEP of UE-1 in the multi-user MIMO mode as per system equation (1). Let $\mathbf{p}_1 = [1 \;\; q]^T$ where $q \in \{\pm 1, \; \pm j\}$. To have good channel separation between the UEs to be served in the multi-user MIMO mode [6], scheduling at the eNodeB would ensure $\mathbf{p}_2$ to be $[1 \;\; -q]^T$. The effective channel seen by the desired stream $x_{1,k}$ at UE-1 is given as $h_{1,k} = h^*_{11,k}+qh^*_{21,k}$ whereas the channel seen by the interference stream $x_{2,k}$ is $h_{2,k} = h^*_{11,k}-qh^*_{21,k}$. The max log MAP bit metric is written as

$$\lambda_1^i\left(y_{1,k}, c_{k'}\right) \approx \min_{x_1 \in \chi^i_{1,c_{k'}}, x_2 \in \chi_2} \frac{1}{N_0}\left|y_{1,k}-\frac{1}{\sqrt{4}}h_{1,k}x_1-\frac{1}{\sqrt{4}}h_{2,k}x_2\right|^2$$

Conditional PEP i.e $P(\mathbf{c}_1 \to \hat{\mathbf{c}}_1|\mathbf{h}_1) = P^{\hat{\mathbf{c}}_1}_{\mathbf{c}_1}$ is given as

$$P^{\hat{\mathbf{c}}_1}_{\mathbf{c}_1} = P\left(\sum_{k'}\min_{x_1 \in \chi^i_{1,c_{k'}}, x_2 \in \chi_2}\frac{1}{N_0}\left|y_{1,k}-\frac{1}{\sqrt{4}}h_{1,k}x_1-\frac{1}{\sqrt{4}}h_{2,k}x_2\right|^2 \right.$$
$$\left. \geq \sum_{k'}\min_{x_1 \in \chi^i_{1,\bar{c}_{k'}}, x_2 \in \chi_2}\frac{1}{N_0}\left|y_{1,k}-\frac{1}{\sqrt{4}}h_{1,k}x_1-\frac{1}{\sqrt{4}}h_{2,k}x_2\right|^2\right) \quad (9)$$

Let's denote

$$\tilde{x}_{1,k}, \tilde{x}_{2,k} = \arg\min_{x_1 \in \chi^i_{1,c_{k'}}, x_2 \in \chi_2}\frac{1}{N_0}\left|y_{1,k}-\frac{1}{\sqrt{4}}h_{1,k}x_1-\frac{1}{\sqrt{4}}h_{2,k}x_2\right|^2$$
$$\hat{x}_{1,k}, \hat{x}_{2,k} = \arg\min_{x_1 \in \chi^i_{1,\bar{c}_{k'}}, x_2 \in \chi_2}\frac{1}{N_0}\left|y_{1,k}-\frac{1}{\sqrt{4}}h_{1,k}x_1-\frac{1}{\sqrt{4}}h_{2,k}x_2\right|^2 \quad (10)$$

Note that

$$\left|y_{1,k}-\frac{1}{\sqrt{4}}(h_{1,k}x_{1,k}+h_{2,k}x_{2,k})\right|^2 \geq \left|y_{1,k}-\frac{1}{\sqrt{4}}(h_{1,k}\tilde{x}_{1,k}+h_{2,k}\tilde{x}_{2,k})\right|^2$$

So conditional PEP is given as

$$P^{\hat{\mathbf{c}}_1}_{\mathbf{c}_1} \leq Q\left(\sqrt{\sum_{k,d_{free}}\frac{1}{8N_0}\left|h_{1,k}(x_{1,k}-\hat{x}_{1,k})+h_{2,k}(x_{2,k}-\hat{x}_{2,k})\right|^2}\right)$$
$$= Q\left(\sqrt{\sum_{k,d_{free}}\frac{1}{8N_0}\left|\mathbf{h}_k^T(\mathbf{x}_k-\hat{\mathbf{x}}_k)\right|^2}\right) \quad (11)$$

where $\mathbf{h}_k = \left[h^*_{11,k} \;\; qh^*_{21,k} \;\; h^*_{11,k} \;\; -qh^*_{21,k}\right]^T$, $\mathbf{x}_k = [x_{1,k} \;\; x_{1,k} \;\; x_{2,k} \;\; x_{2,k}]^T$ and $\hat{\mathbf{x}}_k = [\hat{x}_{1,k} \;\; \hat{x}_{1,k} \;\; \hat{x}_{2,k} \;\; \hat{x}_{2,k}]^T$. We assume channel to be slow fading, i.e. the channel remains constant for the duration of one codeword. So the PEP can be written as

$$P^{\hat{\mathbf{c}}_1}_{\mathbf{c}_1} \leq Q\left(\sqrt{\sum_{k,d_{free}}\frac{1}{8N_0}\left|\mathbf{h}^T(\mathbf{x}_k-\hat{\mathbf{x}}_k)\right|^2}\right)$$
$$= Q\left(\sqrt{\frac{1}{8N_0}\mathbf{h}^\dagger\mathbf{\Delta\Delta}^\dagger\mathbf{h}}\right) \quad (12)$$

where $\mathbf{\Delta\Delta}^\dagger$ is a 4×4 matrix while $\mathbf{\Delta}_{4\times d_{free}} = \left[\mathbf{x}_1-\hat{\mathbf{x}}_1 \; \mathbf{x}_2-\hat{\mathbf{x}}_2 \; \cdots \; \mathbf{x}_{k,d_{free}}-\hat{\mathbf{x}}_{k,d_{free}}\right]$. Using Chernoff bound, (12) is upper bounded by

$$P(\mathbf{c}_1 \to \hat{\mathbf{c}}_1|\mathbf{h}) \leq \frac{1}{2}\exp\left(-\frac{1}{16N_0}\mathbf{h}^\dagger\mathbf{\Delta\Delta}^\dagger\mathbf{h}\right) \quad (13)$$

The covariance matrix of the channel $\mathbf{h}$ is

$$E\left[\mathbf{hh}^\dagger\right] = \mathbf{R} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 \\ 1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix} \quad (14)$$

Its rank is two with its two identical eigenvalues being 2. Using the moment generating function of a Hermitian quadratic form in complex Gaussian random variable, we get

$$E_{\mathbf{h}}\left[\frac{1}{2}\exp\left(-\frac{1}{16N_0}\mathbf{h}^\dagger\mathbf{\Delta\Delta}^\dagger\mathbf{h}\right)\right] \leq \frac{1}{2\det\left(\mathbf{I}+\frac{1}{16N_0}\mathbf{R\Delta\Delta}^\dagger\right)} \quad (15)$$

Note that the minimizations in (10) ensure that in $\mathbf{\Delta}$, $\hat{x}^{'}_{1,k}-x^{'}_{1,k}$ is always non-zero where $\hat{x}^{'}_{2,k}-x^{'}_{2,k}$ can be zero for $k = 1, \cdots, d_{free}$. So in the worst case scenario, $\mathbf{\Delta}$ would have only first two rows with non-zero elements. For the high SNR approximation, we get

$$\mathcal{P}^{\hat{\mathbf{c}}_1}_{\mathbf{c}_1} \leq \frac{1}{2}\left(\frac{16N_0}{\sigma^2}\right)^r\prod_{k=1}^{r}\frac{1}{\mu_k} \quad (16)$$

where r is the rank and μ_k are the eigenvalues of $\mathbf{R\Delta\Delta}^\dagger$. The minimum rank is one thereby indicating the diversity order of one. Note that as the derivation has involved Chernoff bound, so the exact PEP expression would involve some additional multiplicative factors but these factors will not affect the diversity order.

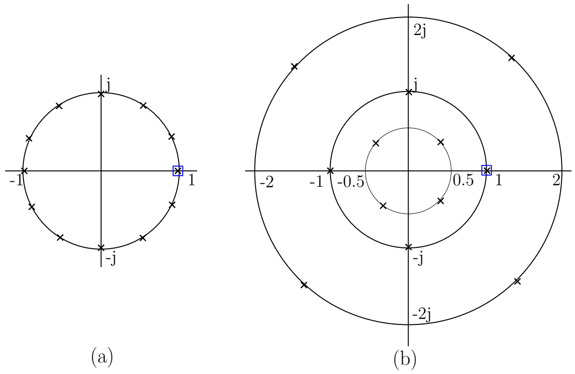

Fig. 1. Two options of increasing the precoder codebook size. Fig.(a) corresponds to the option of increased angular resolution of LTE precoders while Fig.(b) corresponds to the option of enhanced levels of transmission. Square indicates the precoder entry for the first antenna while cross indicates the precoder entry for the second antenna.

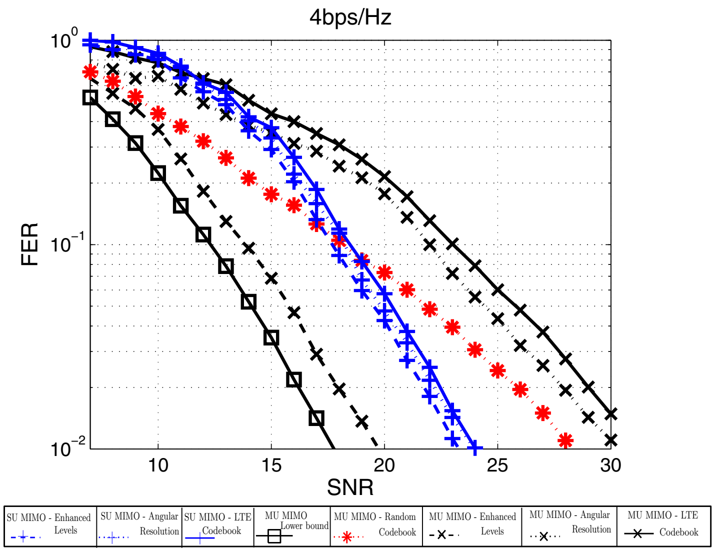

Fig. 2. Proposed precoder codebook. Downlink channel with dual-antenna eNodeB and two single-antenna UEs. The figure illustrates the performance for the sum rate of 4bps/Hz. SNR is the transmit SNR while sum rate is same for single-user and multi-user MIMO, i.e. if two UEs are served with QPSK, rate $1/2$, in multi-user mode, then one UE is served with QAM16, rate $1/2$, in the single-user mode. SU MIMO and MU MIMO indicate single-user and multi-user MIMO.

IV. The Proposed Feedback and Codebook design

It was shown in the PEP analysis that the multi-user MIMO mode in LTE suffers from a loss of diversity. This loss is mainly attributed to the EGT characteristic of these precoders as will be shown in the next section. On the other hand, this transmission characteristic does not affect the diversity order in single-user MIMO mode. Focusing on this result, we propose a design of LTE precoders to offset this diversity loss.

LTE precoders are characterized by two features, i.e. angular resolution and EGT. Limited increase in the feedback can be either employed to increase the angular resolution of these structured precoders or it can be used to enhance the levels of transmission. Increasing the levels of transmission implies that additional feedback bits can be used to indicate an increase of the power level on either of the two antennas, i.e. creating more circles with different radii. For this we resorted to numerical optimization for fixing the radii of two circles and the precoders turn out to be $[1 \quad 2\exp(j\theta)]^T$ or $[2\exp(j\theta) \quad 1]^T$ where $\theta \in \{0, \pm 90°, 180°\}$. This approach gives 8 additional codebook entries, and 12 in total. Improving angular resolution is trivial, i.e. increasing equally angular spaced points on the unit circle but restricting to EGT, i.e. precoder is given as $[1 \quad \exp(j\theta)]^T$, where $\theta = 2\pi l/12, l = 0, \ldots, 11$. These two different codebook options have been illustrated in Fig. 1.

To quantize the proposed codebooks of size 12, $\lceil \log_2(12) \rceil = 4$ bits are needed. That means that we could add 4 more additional codebook entries for free, but it is not obvious how those extra entries should be designed in the case of the codebook with the additional transmission levels. On the other hand it can be argued that several PMI feedbacks (for example for different subbands) can be bundled to optimize the feedback rate.

V. Simulation Results

For the simulations, we consider the downlink of LTE and LTE-Advanced (BICM OFDM transmission). The eNodeB is equipped with two antennas using a punctured rate-$1/3$ LTE turbo code. We focus on the multi-user MIMO mode and consider single-antenna UEs. We carry out two sets of simulations where the first set focuses on the performance of proposed codebook design in i.i.d fading channels whereas the second set focuses on the performance in realistic 3GPP LTE channel models [7]. We assume no power control in the multi-user MIMO mode so the eNodeB allocates equal power to the two UEs. It is assumed that the UE knows its own channel from the eNodeB and the effective channel of the interference (co-scheduled UE). The UEs employ low-complexity interference-aware receivers [8].

Fig. 2 shows the first set of simulations where we consider an ideal OFDM system (no ISI) and analyze the system in the frequency domain with the channel entries being i.i.d. Gaussian with unit variance. We consider slow fading, i.e. the channel remains constant for the duration of one codeword. We focus on the frame error rates (FER) where the frame length is fixed to 1056 information bits. These results show significant improvement in the performance of the multi-user MIMO mode when additional codebook entries are employed to increase the levels of transmission as compared to the case of increasing the angular resolution of precoders. However creating two levels of transmission leads to significant improvement as the performance moves closer to the upper bound. This hypothetical upper bound is the performance curve for MF precoder in multi-user MIMO mode without any interference, i.e. the eNodeB serves two UEs with their respective MF based precoders and the two UEs do not see any interference. The change of the slope of FER curve with increased levels of transmission indicates improved diversity as compared to the case of increased angular resolution. On the other hand, little gain is observed in the single-user mode (LTE transmission mode 6) with additional codebook entries which is expected as the standard LTE precoders have been optimized for the single-user transmission [3]. For comparison purposes, we have also considered the case of random codebooks. The main advantage of random codebooks is that they indicate some sort of performance lower bound and with any intelligent feedback design, system is bound to perform better.

Fig. 3 shows the second set of simulations where we have considered 3GPP LTE channel model introduced in [7] for three representative scenarios, i.e. pedestrian, vehicular and typical urban scenario. The transmission chain is dominantly LTE compliant with 15 KHz subcarrier-spacing and 20 MHz system bandwidth. The results confirm the earlier findings of the improved performance of proposed codebook design (enhanced levels of transmission) for multi-user transmission mode. Pedestrian channel offers less diversity in the channel as compared to the vehicular channel, so the performance of LTE precoders for multi-user MIMO in severely degraded in the former case. However as the proposed precoder design recovers the lost order of diversity, there is an improvement of 6dB at the target FER of 10^{-1}.

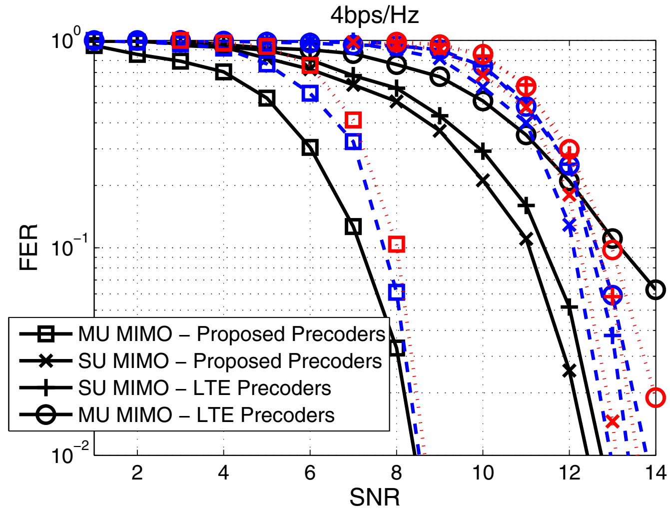

Fig. 3. Performance of the proposed precoder codebook in 3GPP LTE channel models [7]. Black continuous lines show the Extended Pedestrian A model (EPA), blue dashed lines show Extended Vehicular A model (EVA), while red dotted lines show Extended Typical Urban model (ETU).

VI. Discussion

These results give a guideline for the feedback and precoder design indicating that the constant modulus property of LTE precoders has to be forfeited in order to realize the gains of multi-user MIMO. Note that these results do not under-emphasize the significance of phase information in the feedback rather they underline that the magnitude information also needs to be accounted for in the feedback and precoder design. This proposed design is not restricted to the future releases of LTE rather it can also be used in transmission modes 8 and 9 in LTE-Advanced where eNodeB has the freedom to choose any precoder. The proposed design is also important in a Time Division Duplex (TDD) based LTE system where channel reciprocity can be exploited for channel estimation at eNodeB. Due to uncertainties in the analogue and RF parts of the transceivers, improved phase granularity is very hard to estimate through reciprocity. On the other hand, the proposed codebook mainly requires estimating the differences between the channel gains on the two antennas with low level phase information, which is much easier to estimate. These results can be extended to the case of 4 transmit antennas where LTE standardized codebook comprises of points on a unit sphere. Performance will be significantly improved if the additional feedback bits are used to create more spheres rather than enhancing the angular resolution of the unit sphere. Though scheduling has been incorporated in multi-user mode [9], we have not incorporated link adaptation in the simulations. Link adaptation will surely lead to further improvement in the performance but it will not modify the basic conclusion of the necessity of more transmission levels to realize the gains of multi-user MIMO in future wireless systems.

VII. Conclusions

In this paper, we have investigated the impact of low-level fixed rate feedback on the performance of multi-user MIMO in LTE systems. To this end, we have proposed a feedback and precoding design and have shown that the performance in multi-user MIMO significantly improves once strategy of more levels of transmission is resorted to as compared to the case of increased angular resolution. The work presented in this paper is not merely confined to the framework of LTE, rather it gives the feedback and precoding design guidelines for modern wireless systems which all acquire CSIT through limited feedback.

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