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Abstract	When the channel is correlated in time or in frequency, e.g., across different tones, the correlation can be used to considerably reduce the feedback requirement without loss in performance. The idea of multi-resolution codebook is to feedback only the variation in the channel, since typically quantizing the channel variations requires a smaller codebook than quantizing the channel itself.
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Multi-resolution Precoding Codebook

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1 Introduction

The next generation wireless communication systems demand for even higher spectral efficiencies to accommodate the higher throughput requirements within the limited frequency bands. Multiple antenna (MIMO) systems and in particular closed loop transmission technologies such as beamforming and precoding have been vastly considered to improve the spectral efficiency. In MIMO precoding schemes, the transmitted data is divided into several independent streams where each streams is individually precoded and all precoded streams are superimposed before transmission. The number of transmitted streams is called transmission rank. The transmission rank can be optimally chosen for a given channel realization by considering the transmit power and the overall channel statistics. For each stream the precoder is a beamforming vector which consists of a set of weights, one for each antenna, that are multiplied with the transmitted symbol prior to the transmission.

the precoder of rank r is then a matrix consists of r beamforming vectors as its columns. Generally, the average transmit power is divided equally between all streams, thus, the norm of all beamforming vectors are equal and normalized to one. Furthermore, due to the superposition of the transmitted streams, the beamforming vectors are chosen to be orthogonal for simplicity of the decoding. As a result, the precoder is generally a semi-unitary matrix[1].

In codebook based precoding strategies, a predetermined codebook will be made available to the transmitter, i.e., Base Station (BS), and all receivers, i.e., Mobile Stations (MS). The receiver will then choose a precoder from the codebook which maximizes its performance (e.g. its data rate) and feeds back the precoder index. The selection of precoder rank should also be included in the precoder selection algorithm. The feedback rate may vary from a short-term feedback once every coherent time interval to a long-term feedback once every several coherent time intervals.

In many systems, the optimal precoders from the codebook for two adjacent transmission blocks are close with respect to a proper distance measure in the set of all possible precoders. Here, the adjacent blocks may be considered in time or in frequency, e.g., over the set of tones in OFDM systems. The intuition behind this statement is that in a practical systems the channel does not change abruptly from one transmission block to the adjacent one. Thus, the precoder used in those blocks should be equal if the channel is pretty steady and the codebook resolution is not two high. By increasing the codebook resolution or having a more dynamic channel, the precoders of the adjacent blocks are not equal anymore, yet, they might be close. The closeness between two precoders can be measured based on a proper distance metric in the space of all such precoders. This fact motivates the concept of multi-resolution codebook discussed in Section 3.2.

The remainder of this paper is organized as follows. In Section 2, we describe the system, the channel model and the notations used in this paper. In Section 3, we present the precoding codebook designs. The simulation setup and the numerical results are discussed in Section 4, and Section 5 contains the conclusions.

2 System Description

We consider a downlink multiuser MIMO system with N_T transmit antennas at the BS and N_R receive antennas at MS. We model the baseband fading channel linking the i^{th} transmit to the p^{th}

[1] $\mathbf{V}_{n\times r}, r \leq n$ is called semi-unitary iff $\mathbf{V}^H\mathbf{V} = \mathbf{I}$.

receive antenna as a finite impulse response (FIR) filter with L taps

$$h_{ip} = \sum_{l=1}^{L} \alpha_{ip}(l)\delta(t - \tau_{ip}(l)), \ \ i = 1, \ldots, N_T, \ \ p = 1, \ldots, N_R, \qquad (1)$$

where $\alpha_{ip}(l)$ is the complex gain and $\tau_{ip}(l)$ is the delay of the l^{th} path. We assume that OFDM is employed to convert the underlying frequency-selective channels to a set of M_T narrowband tones. Thus, the equivalent complex baseband model for the c^{th} channel corresponding to the c^{th} subcarrier can be expressed as

$$\mathbf{y}_c = \sqrt{P/N_T}\mathbf{H}_c\mathbf{x}_c + \mathbf{w}_c, , \ \ c = 1, \ldots, M_T, \qquad (2)$$

where $\mathbf{x}_c$ is the $N_T \times 1$ transmitted signal vector, $\mathbf{H}_c$ is the $N_R \times N_T$ channel matrix, $\mathbf{w}_c \sim \mathcal{N}_c(\mathbf{0}, \mathbf{I})$ is a circularly symmetric additive white complex Gaussian noise vector, and $\mathbf{y}_c$ is the $N_R \times 1$ received signal vector. Using (1), the frequency response $\mathbf{H}_c$ of the MIMO channel at the c^{th} subcarrier is given by

$$(H_c)_{ip} = \sum_{l=1}^{L} h_{ip}(lT_s)e^{-j2\pi lc/M_T} \simeq \sum_{l=1}^{L} \alpha_{ip}(l)e^{-j2\pi c\tau_{ij}(l)/T_s} \qquad (3)$$

where T_s and $\Delta f = 1/T_s$ are the OFDM symbol period and the subcarrier frequency separation, respectively. We consider a block fading channel model in which the channel remains constant during the transmission of each packet (or codeword of length T) and it changes independently from one block to another. The distributions of $\{\alpha_{ip}(l), \tau_{ij}(l)\}$ in (1) are modeled according to [1, 2]. We assume that $\mathbb{E}[\mathbf{x}_c^*\mathbf{x}_c] \leq 1$ in (2); thus, the average transmit power on c^{th} subcarrier in an OFDM block is denoted by P independent of the number of transmit antennas.

We consider maximizing the sum-rate throughput which is usually the primary goal in downlink transmissions [8, 7, 6, 9, 5]. We make the following assumptions: (1) the channel is known at the receiver perfectly; (2) the quantized channel state for each user is provided to the transmitter via a feedback link of limited rate; and (3) only linear precoding is allowed at the BS. We assume that the feedback link is error-free and has zero-delay.

In order to minimize the feedback rate, the quantized channel state information is fed back for a group of adjacent OFDM tones, referred to as a resource block (RB), and only one precoder is used for each RB. Such per RB precoding can be justified for systems where the number of tones is much larger than the number of multi-paths, i.e., $M_T \gg L$. In such cases, the optimal precoders for adjacent OFDM tones are very close and usually identical considering the finite (coarse) precision of the precoding codebook. We assume M_B resource blocks, each consisting of M_D/M_B adjacent OFDM tones, where M_D OFDM tones are used for the data transmission and the remaining $M_T - M_D$ OFDM tones are reserved for transmitting the control and signaling information.

The feedback information from MS consists of three parts: (1) The precoding rank $r \leq N_T$ which is the number of independent streams that can be transmitted; (2) the precoder matrix index (PMI) from a predesigned codebook; and (3) the CQI that represents the signal-to-interference-plus-noise-ratio (SINR) for each stream.

Based on the quantized feedback received from the MSs, the BS then schedules the appropriate MS for transmission in each RB and chooses a precoder which is an $N_T \times r$ matrix $\mathbf{Q}_n$ from a predesigned precoding codebook $\mathcal{Q}$. The transmitted signal vector is then obtained by precoding r coded QAM symbols $\mathbf{u} = [u_1, u_2, \dots u_r]$, i.e., $\mathbf{x}_n = \mathbf{Q}_n \mathbf{u}_n$. The outer code used in this paper is the IEEE 802.16e convolutional turbo code (CTC) [3] and for ease of exposition we assume that only one codeword is transmitted to a scheduled MS by coding across all the tones assigned to that MS. The design of the precoding codebook $\mathcal{Q}$ is discussed in Section 3. It should be noted that for a practical system the performance of the precoder selection algorithm may be enhanced by considering the receiver structure (e.g., LMMSE or SIC) and calculate the achievable rate accordingly.

To further optimize the feedback load, we consider providing feedback for the set of M adjacent resource blocks (RBs) by using a multi-resolution codebook. In this case, we use a low-resolution codebook and find an precoder index which is optimal for all RBs. Then, we provide a resolution information for each RB by using high-resolution codebook. In case that we use a nested multi-resolution codebook as defined in Section 3.2, the procedure may be further enhanced by applying a successive approach. In this case, we first find the low-resolution precoding index for the center RB. Then, we provide a refinement index for the center RB by using high-resolution codebook. Next, we consider the two adjacent RBs and only calculate the precoder index from high-resolution codebook assuming the low-resolution index for these two blocks are the same as the high-resolution precoder index for the center RB. This procedure is performed successively for the next two adjacent RBs by where for each one the previously calculated precoder index for the adjacent cell is used as the low-resolution index, and so on.

3 Precoding Codebook

In this section, we discuss the precoding codebook design. First, we briefly address the conventional codebook design in which only one precoder index is fed back for the resource blocks (RBs) and different RBs are treated individually. Such codebook can also be used to report a single precoding index for a group of RBs. Next, we present multi-resolution codebook, where for a group of adjacent RBs, the precoder selection algorithm first selects a common precoder index from a low-resolution codebook and then for each RBs within the group a high-resolution codebook is used to fine tune the precoders for each RB. Thus, in this work, the conventional codebook is referred to as the single-resolution codebook.

The concept of multi-resolution codebook may be extended to multiple level of codebook resolution. Nonetheless, in this work, we primarily focus on the multi-resolution codebooks with only two resolution levels: the low-resolution and the high-resolution. It will be shown that by using such multi-resolution codebook similar performance can be achieved with lower feedback load in comparison to a system using a single-resolution codebook. Furthermore, both single-resolution or multi-resolution require almost similar memory to store the codebooks and the complexity of the precoder selection using either of the codebooks is also comparable.

3.1 Single-resolution codebook

We drop the subscript c in this section and let $\mathbf{H}$ denote the channel matrix of any subcarrier. For a resource block, we generally use the channel matrix of the center tone for the sake of precoder selection. For a given transmission rank r and B bits of PMI feedback, the codebook design problem is formulated as finding the set $\mathcal{Q} = \{\mathbf{Q}_1, \mathbf{Q}_2, \ldots, \mathbf{Q}_{2^B}\}$ of $N_T \times r$ semi-unitary matrices that is a solution to the optimization problem given by

$$C = \max_{\mathcal{Q}} \ \mathbb{E}\left[\max_{\mathbf{Q}\in\mathcal{Q}} \ \log\det\left(\mathbf{I} + \frac{P}{N_T}\mathbf{H}\mathbf{Q}\mathbf{Q}^*\mathbf{H}^*\right)\right]. \tag{4}$$

Conventionally, the maximization problem is solved by equivalently minimizing the chordal distance between the dominant right singular vectors of the channel and the corresponding quantized vectors, where the chordal distance is defined as

$$d_{chordal}(\mathbf{Q}, \mathbf{V}) = \frac{1}{\sqrt{2}}||\mathbf{V}\mathbf{V}^* - \mathbf{Q}\mathbf{Q}^*||_F = \sqrt{N_T - ||\mathbf{V}^*\mathbf{Q}||_F^2}. \tag{5}$$

and $\mathbf{U}\mathbf{D}\mathbf{V}^*$ is the partial SVD of $\mathbf{H}$ obtained by retaining only the r right singular vectors that correspond to the r largest singular values of $\mathbf{H}$. Other distance metric such as Fubini-study metric and p-metric defined between the subspaces $\mathbf{V}$ and $\mathbf{Q}$ on the Grassmanian manifold $G(N_T, r)$ may also be used.

If a single-resolution codebook is used, the precoder $\mathbf{Q}$ for the channel $\mathbf{H}$ is obtained from the codebook $\mathcal{Q}$ such that $\log\det\left(\mathbf{I} + \frac{P}{N_T}\mathbf{H}\mathbf{Q}\mathbf{Q}^*\mathbf{H}^*\right)$ is maximized. This capacity measure may be modified accordingly depending on the type of the receiver structure, e.g., if LMMSE is used.

3.2 Multi-resolution codebook

In a multi-resolution codebook, the codebook $\mathcal{Q} = \{\mathcal{Q}_1, \mathcal{Q}_2, \ldots, \mathcal{Q}_q\}$ consists of q codebooks where the codebook $\mathcal{Q}_{i+1}$ is used to add more resolution to the prior set of codebooks $\mathcal{Q}_1, \ldots, \mathcal{Q}_i$. By using a multi-resolution codebook, finding the optimal precoder for a given channel realization $\mathbf{H}$ is performed as follows. First, we find the optimal precoder $\mathbf{Q}_1(\mathbf{H}) \in \mathcal{Q}_1$ for a given channel realization $\mathbf{H}$. Then, we find the optimal precoder $\mathbf{Q}_2(\mathbf{H}, \mathbf{Q}_1) \in \mathcal{Q}_2$ that depends both on the previous precoder $\mathbf{Q}_1$ and the channel matrix $\mathbf{H}$. Depending on the required resolution, this action is successively performed to find, e.g., the precoder $\mathbf{Q}_i(\mathbf{H}, \mathbf{Q}_1, \ldots, \mathbf{Q}_{i-1}) \in \mathcal{Q}_i$, $i \leq q$. It should be pointed out that the multi-resolution codebook is optimized based on the channel statistics. In general, different resolution may be optimized for different channel statistics. For example, in an OFDM systems, the first codebook $\mathcal{Q}_1$ may be optimized by considering the statistics of the center tone in any RBs, and the second codebook $\mathcal{Q}_2$ may be optimized by considering the statistics of the adjacent RBs as well.

For a simpler discussion, we assume $q = 2$ and consider only one low-resolution codebook $\mathcal{Q}_1$ and one high-resolution codebook $\mathcal{Q}_2$. In the sequel, we provide two examples of the multi-resolution codebook designs: the multi-resolution codebook based on partitioning and the multi-resolution codebook based on the unitary rotation.

Multi-resolution codebook based on partitioning

For a simple construction of a multi-resolution codebook, we can use a partitioning concept. Let $\mathcal{K}$ denote a single-resolution codebook of size $|\mathcal{K}|$ which has designed to meet the highest required resolution. To generate a multi-resolution codebook, we first find a low-resolution codebook $\mathcal{Q}_1$ by taking $|\mathcal{Q}_1|$ elements form $\mathcal{K}$ which have the maximum minimum distance between each two element. For each element $\mathbf{Q}_i$ of the codebook $\mathcal{Q}_1$, we then find the set of *closest* $|\mathcal{K}|/|\mathcal{Q}_1|$ elements from $\mathcal{K}$ and denote it by $\mathcal{Q}_{2i}$. However, the elements are chosen such that each element of $\mathcal{K}$ belongs to one and only one $\mathcal{Q}_{2i}$. Please note that the set $\mathcal{Q}_2 = \{\mathcal{Q}_{21}, \mathcal{Q}_{22}, \ldots, \mathcal{Q}_{2,|\mathcal{Q}_1|}\}$ eventually includes all the elements of $\mathcal{K}$ but each element is doubly indexed, i.e., an index corresponding to a unique element of $\mathcal{Q}_1$ and an index which enumerate the possible choices of the precoders in $\mathcal{Q}_2$ for a given precoder index in $\mathcal{Q}_1$. Thus, the set $\mathcal{Q}_2$ is divided into $|\mathcal{Q}_1|$ partitions such that each partition $\mathcal{Q}_{2i}$ has equal number of elements. It should also be noted that such partitioning is not unique, because the set of *closest* elements depends on the order that we assign the elements of $\mathcal{K}$ to each partition. Thus, an optimization may be performed to maximize the overall codebook performance by taking the best partitioning.

An alternative approach to design a multi-resolution codebook is to first design a low-resolution codebook $\mathcal{Q}_1$ directly. Next, for each entry of the codebook, say $\mathbf{Q}_i$, we find the set of channel conditions for which this entry is chosen and denote it as $\mathcal{H}(\mathbf{Q}_i)$. Then, we design an optimal codebook $\mathcal{Q}_{2i}$ using only the channel conditions in $\mathcal{H}(\mathbf{Q}_i)$, i.e., solving the optimization problem (4) where the expectation is taken over $\mathcal{H}(\mathbf{Q}_i)$. The size of $\mathcal{Q}_{2i}$ is chosen to meed the desired resolution level. The codebook $\mathcal{Q}_2 = \{\mathcal{Q}_{21}, \mathcal{Q}_{22}, \ldots, \mathcal{Q}_{2,|\mathcal{Q}_1|}\}$ is then constructed as the set of all such designed codebooks.

In some cases, it is beneficial to design a nested multi-resolution codebook. The codebook $\mathcal{Q} = (\mathcal{Q}_1, \mathcal{Q}_2)$ is called *nested multi-resolution codebook* if and only if

$$\forall i, 1 \leq i \leq |\mathcal{Q}_1| : \mathcal{Q}_{2i} \subset \mathcal{Q}_1 \tag{6}$$

One possible design can be obtained by taking the low-resolution codebook $\mathcal{Q}_1 = \mathcal{K}$ and then find the set of $\mathcal{Q}_{2i} \subset \mathcal{K}$ as the $\mathcal{Q}_{2i}|$ closest neighbors of each elements $\mathbf{Q}_i \in \mathcal{Q}_1$ to construct the high-resolution codebook $\mathcal{Q}_2 = \{\mathcal{Q}_{2i}\}_{i=1}^{|\mathcal{Q}_1|}$. In this case, the high-resolution codebook does not increase the resolution for the original RB, but successive application of this codebook for the adjacent RBs considerably improves the resolution of the precoder matrix for the adjacent RBs.

Please note that the representation of the latter codebook constructions requires storing $|\mathcal{Q}_1|$ and $|\mathcal{Q}_2|$ precoders and a set of indices to denote the partitioning in $\mathcal{Q}_2$. Also, the former codebook construction needs storing $|\mathcal{K}|$ precoders plus two set of indices to represent $\mathcal{Q}_1$ and $\mathcal{Q}_2$ codebooks.

Multi-resolution codebook based on unitary rotation

To simplify the codebook storage, we may use functions, $f_i, 1 \leq i \leq |\mathcal{Q}_{2k}|$ which convert each element $\mathbf{Q}_1 \in \mathcal{Q}_1$ to a new precoder of the same size. An example of such function is a unitary rotation, i.e., $\mathbf{Q}_2 = f_i(\mathbf{Q}_1) = \mathbf{F}_i\mathbf{Q}_1$. For the precoder of size $N_T \times r$, the unitary rotations $\mathbf{F}_i$ are of size $N_T \times N_T$. Using such transformation, one needs to store only $|\mathcal{Q}_{2k}|$ unitary matrices that is constant irrespective of k to generate the entire high-resolution codebook $\mathcal{Q}_2$. Thus, the average performance of such generated codebook over all entries of the codebook $\mathcal{Q}_1$ should be considered in the design of the functions f_i. More specifically, we divide the set of all the channel realizations into $|\mathcal{Q}_1|$ partitions $\mathcal{H}(\mathbf{Q}_i), 1 \leq i \leq |\mathcal{Q}_1|$ where the precoder $\mathbf{Q}_i \in \mathcal{Q}_1$ is the optimal precoder.

Thus the codebook design problem is given by

$$\max_{\mathcal{F}} \sum_{i=1}^{|\mathcal{Q}_1|} \mathbb{E}_{\mathcal{H}(\mathbf{Q}_i)} \left[\max_{\mathbf{F}\in\mathcal{F}} \log\det\left(\mathbf{I} + \frac{P}{N_T}\mathbf{H}\mathbf{F}\mathbf{Q}_i\mathbf{Q}_i^*\mathbf{F}^*\mathbf{H}^*\right)\right]. \tag{7}$$

where $\mathcal{F} = \{\mathbf{F}_1, \mathbf{F}_2, \ldots\}$ is the set of unitary matrices that equivalently represent the codebook $\mathcal{Q}_2$.

4 Simulation Results

First, we define the system setup and the codebooks used for the simulations. We assume BS with 4 transmit antennas and a MS with 2 receive antennas. Thus, the precoding schemes use two codebooks of rank 1 and rank 2 with the same size. The rank-1 and rank-2 codebooks for the single-resolution codebook are obtained from IEEE802.16e [3]. An extra feedback bit is also used to feedback the rank of the selected precoder. The PMI of size 3,4,5, or 6 bits represents 8,16,32, or 64 choices for precoders per rank. The single-resolution codebook of size 2^B is denoted by $\mathcal{C}^{(B)}$. The channel model is according to [4] and the other important system parameters are summarized in Table 1.

For the multi-resolution codebook, we use the following cases. For each codebook $\mathcal{C}^{(B)}$, the first set of multi-resolution codebooks $\mathcal{M}^{(B)}$ is obtained by taking the first resolution codebook $\mathcal{M}_1^{(B)} = \mathcal{C}^{(B)}$ and designing a 3-bit unitary rotation codebook $\mathcal{F}^{(B)}$ which equivalently represents $\mathcal{M}_2^{(B)}$.

The second set of multi-resolution codebook $\mathcal{N}^{(B)}, B \geq 5$ is designed by using the partitioning approach. We first find $\mathcal{N}_1^{(B)}$ of size $2^{(B-3)}$ by taking the elements from $\mathcal{C}^{(B)}$ which have the maximum minimum distance from each other. Then, we partition the set $\mathcal{C}^{(B)}$ into $2^{(B-3)}$ where each partition contains the set of 8 closest neighbors for each codebook entry $\mathbf{Q} \in \mathcal{N}_1^{(B)}$. Thus,

$\mathcal{N}_2^{(B)}$ is the set of $\mathcal{C}^{(B)}$ along with the acquired partitioning.

The third set of multi-resolution codebooks $\mathcal{O}^{(B)}$ is also designed by using the partitioning approach. Here, we take $\mathcal{O}_1^{(B)} = \mathcal{C}^{(B)}$ and then we find the set of 8 closest neighbor of each codebook entry $\mathbf{Q}_i \in \mathcal{N}_1^{(B)}$ to obtain $\mathcal{O}_{2i}^{(B)}$, and we have $\mathcal{O}_2^{(B)} = \{\mathcal{O}_{21}^{(B)}, \mathcal{O}_{21}^{(B)}, \ldots, \mathcal{O}_{2,|\mathcal{C}^{(B)}|}^{(B)}\}$.

Please note that, as a point of comparison, the multi-resolution codebook is designed such that only 3 bits is required to represent the high-resolution information about the precoder in all mentioned cases. Thus, the value B in the codebooks $\mathcal{C}^{(B)}$, $\mathcal{M}^{(B)}$, and $\mathcal{O}^{(B)}$ only refers to the size of low-resolution codebook. However, the size of low-resolution codebook in $\mathcal{N}^{(B)}$ is $B-3$ bits.

We compared the throughput performances of the different codebooks through a link level simulation. We use the precoding over M resource blocks of size 24 subcarrier each. When a single-resolution codebook $\mathcal{C}^{(B)}$ is used, the precoder index for each resource block is found individually and total of $6M$ bits is fed back to the BS. However, when the either of the codebooks $\mathcal{M}^{(B)}$, $\mathcal{N}^{(B)}$, and $\mathcal{O}^{(B)}$ is used, the precoding requires B bits for the center resource block and only 3 bits for the rest of $M-1$ resource blocks, thus, the total number of feedback bits is calculated as $6 + 3(M-1) = 3M + 3$.

Figure 1 shows the link level throughput results comparing the single-resolution codebook $\mathcal{C}^{(B)}$ with the multi-resolution codebook $\mathcal{M}^{(B)}$ for various codebook size B. Here, we have used $M = 3$ resource blocks. It is observed that the performance of the multi-resolution codebook is better than that of the single-resolution codebook for $B = 3, 4, 5$ while the feedback load has reduced to $9, 10, 11$ from $9, 12, 15$ bits. The performance of the multi-resolution codebook $\mathcal{M}^{(6)}$ is, however, slightly lower than that of the single-resolution codebook $\mathcal{C}^{(6)}$. Nonetheless, there is a considerable saving of 6 bits in the feedback load in this case.

Figures 2-4 show the link level throughput results comparing the single-resolution codebook $\mathcal{C}^{(B)}$ with the multi-resolution codebook $\mathcal{M}^{(B)}$ for various codebook size B by increasing the number of resource blocks from $M = 3$ to $M = 7$ and $M = 11$. It is observed that the performance of the multi-resolution codebook starts degrading with respect to that of the single-resolution codebook as the M increases. This is due to the fact that we assume the low-resolution index for all M RBs are the same and only calculate the high-resolution indices for the $M-1$ blocks adjacent to the center RB. It is observed that for $M=7$ still the performance of the multi-resolution codebook is better than that of the single-resolution codebook for $B=3$. However, for the $M=11$ the multi-resolution codebook $\mathcal{M}^{(B)}$ shows considerable degradation in performance as it is shown in Figures 4 and 5 . However, one should note that the feedback loads in this case are $36, 35, 34, 33$ instead of $66, 55, 44, 33$ for $B=6, 5, 4, 3$, respectively.

Figure 4 shows the link level throughput results comparing the single-resolution codebook $\mathcal{C}^{(B)}$ with three different design of multi-resolution codebooks, i.e., $\mathcal{M}^{(B)}$, $\mathcal{N}^{(B)}$, and $\mathcal{M}^{(B)}$. In this case we consider $M=11$ resource blocks and only present the result for the codebook size $B=6$. It is seen that although the performance of $\mathcal{M}^{(B)}$ is not so appealing, the performance of the multi-resolution codebook $\mathcal{O}^{(B)}$ is comparable with that of the original single-resolution codebook $\mathcal{C}^{(B)}$. The performance of the other multi-resolution codebook $\mathcal{N}^{(B)}$ is somewhere in between that of $\mathcal{M}^{(B)}$ and $\mathcal{O}^{(B)}$. Thus, by proper design of the multi-resolution codebook, it is possible to achieve a performance close to a single-resolution codebook but with much lower feedback load. In this case, the feedback load has been reduced to 36 from 66 that is a huge saving of 30 bits.

5 Conclusion

When the channel is correlated in time (or in frequency, e.g., across different tones in OFDM systems), the correlation can be used to considerably reduce the feedback requirement without loss in performance. The idea of multi-resolution codebook is to feedback only the variation in the channel, since typically quantizing the channel variations requires a smaller codebook than quantizing the channel itself. Based on the simulation results presented here, we propose the use of multi-resolution codebook for the DL transmission in IEEE802.16m. We have shown that for various number of codebook sizes, the precoding schemes based on the multi-resolution codebook considerably outperforms the ones based on the single-resolution codebook by using the same or reduced feedback load. Moreover, the complexity and memory requirement of such multi-resolution codebook precoding schemes is comparable with those of the conventional single-resolution codebook.

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Parameter	**Assumption**
Access	OFDM
RF carrier frequency	2.0 GHz
Bandwidth	10.0 MHz
Number of paths (Multi-path model)	6
Sub-carrier spacing	10.9375 kHz
Sampling frequency	11.2 MHz
Number of occupied sub-carriers	720
Number of OFDM symbols / frame	47
Frame duration	5ms
Number of subcarriers per slot (RB)	24 x 2 per 2 OFDM symbols
CP length	(1/8)*102.86 micro second
FFT point	1024
Number of antennas at BS	4
Number of antennas at MS	2
Codebook size (in bits)	3,4,5,6 bits for low- resolution, 3 bits for high-resolution
Number of the resource blocks (M)	3,7,11
Channel models	SCM channel model case 1A: 3kmph, L=6
Channel estimation	Ideal channel estimation
MCS	4, 16 and 64 QAM, code rates 1/2, 2/3, 3/4 and 5/6
Quantization codebook	Single-resolution:IEEE802.16e, Multi-resolution:Design

Table 1: Simulation parameters and channel model.

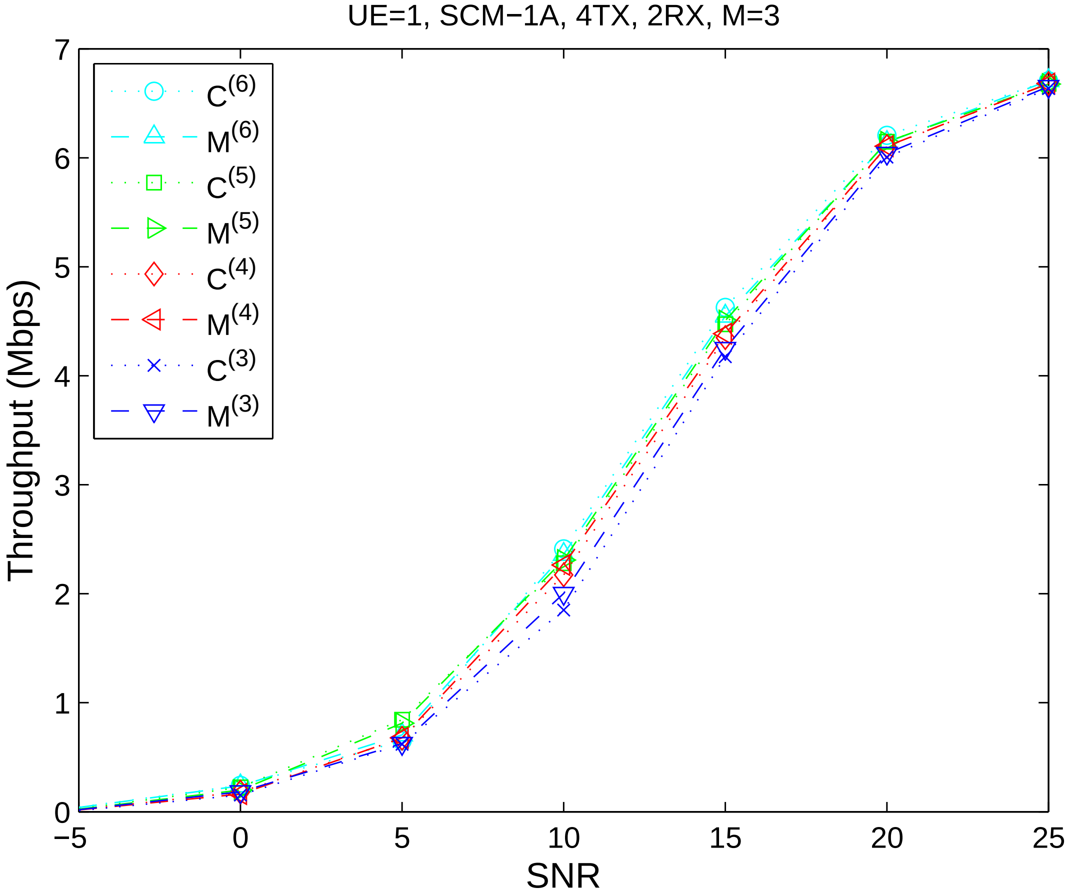

Figure 1: Link level throughput performance over M resource blocks.

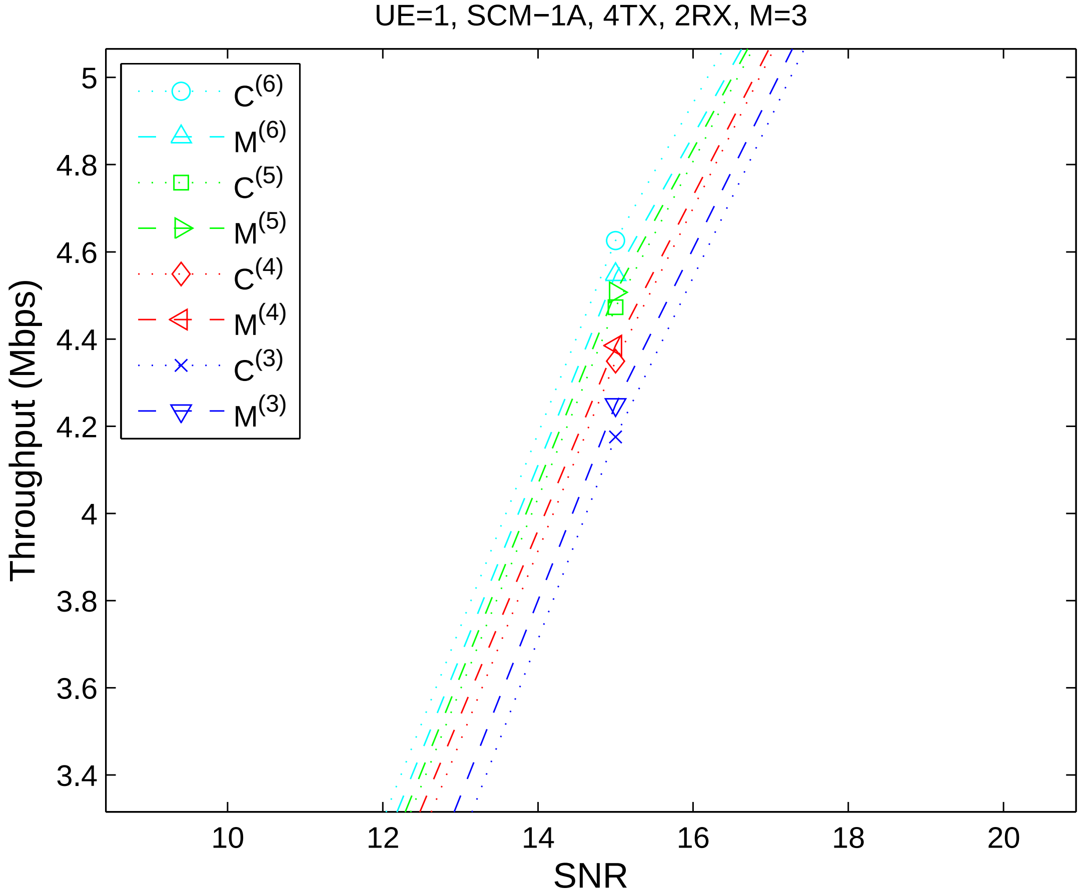

Figure 2: Link level throughput performance over M resource blocks.

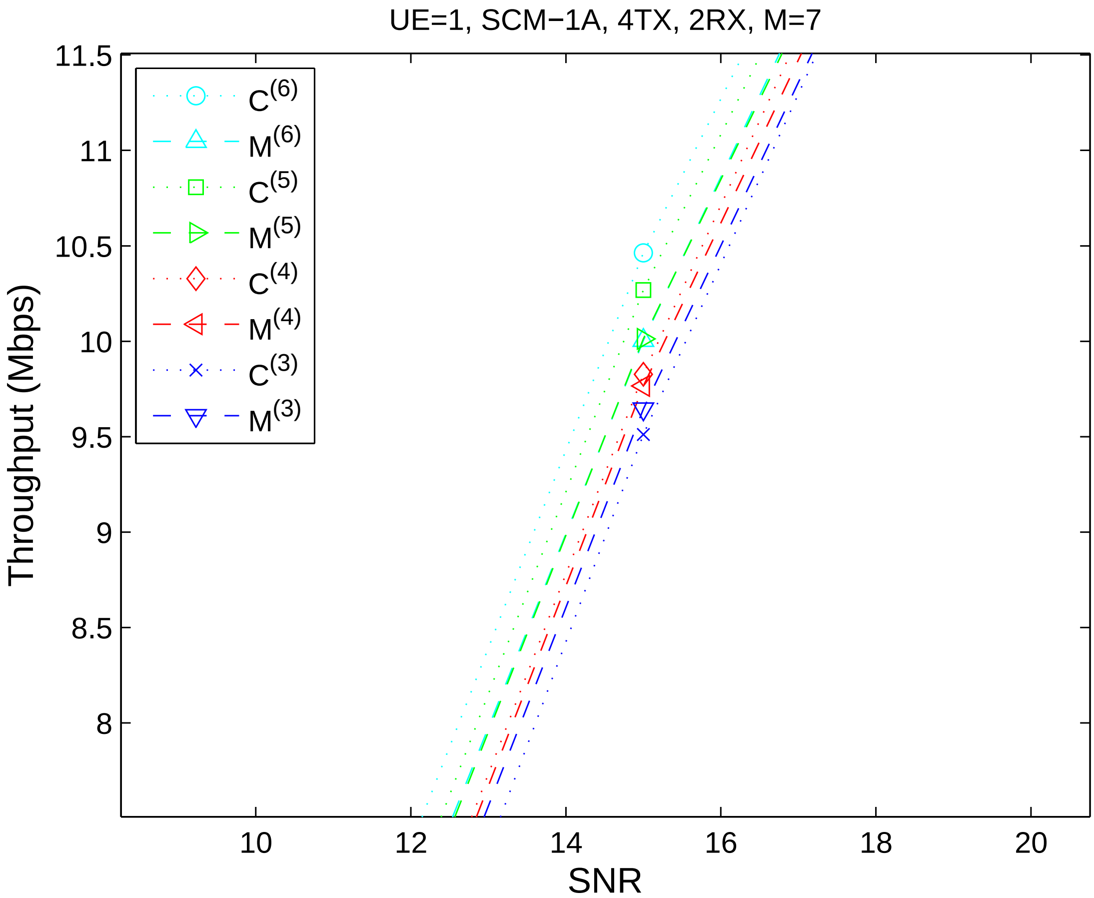

Figure 3: Link level throughput performance over M resource blocks.

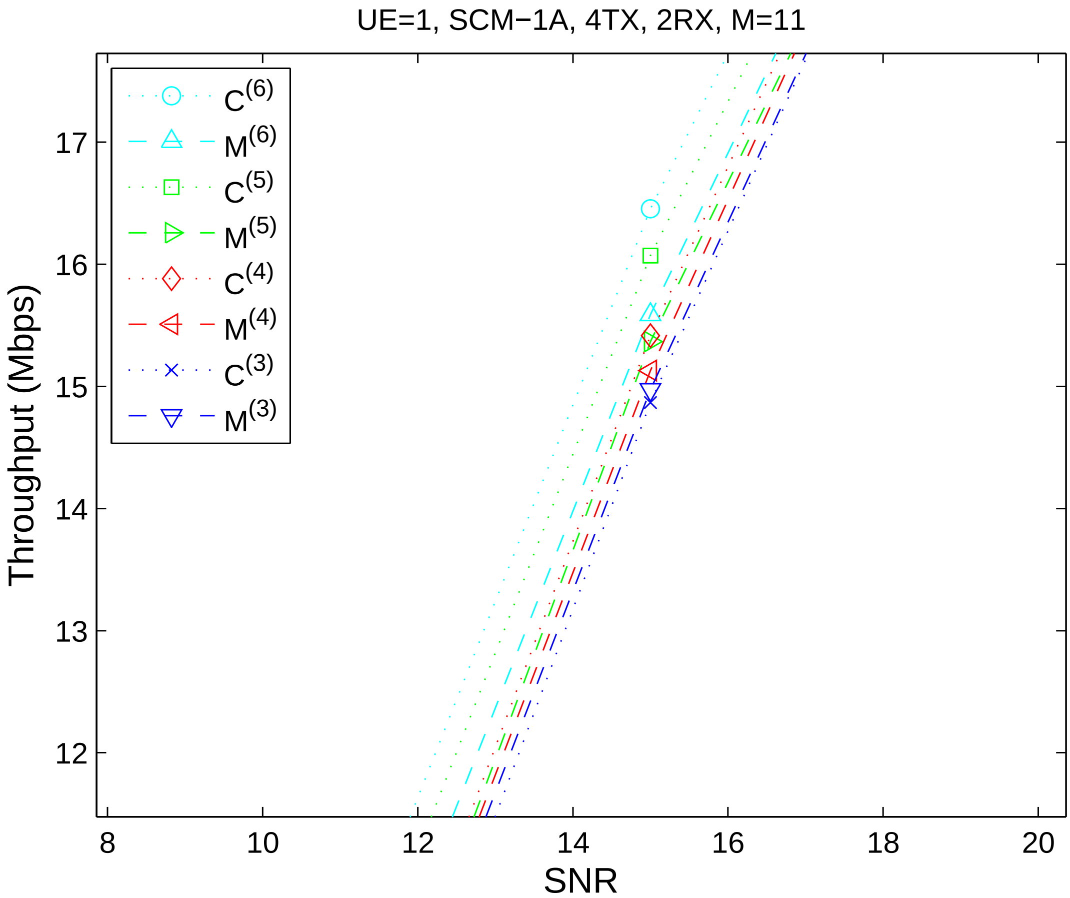

Figure 4: Link level throughput performance over M resource blocks.

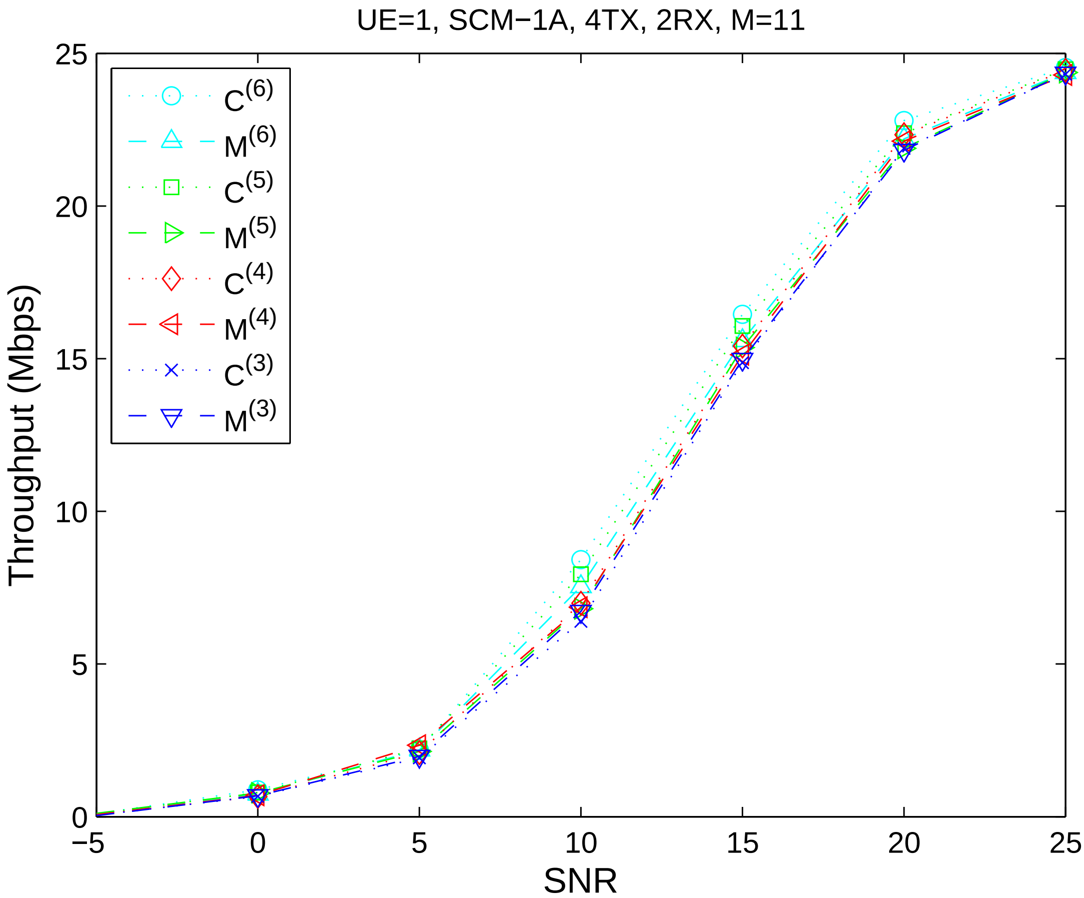

Figure 5: Link level throughput performance over M resource blocks.

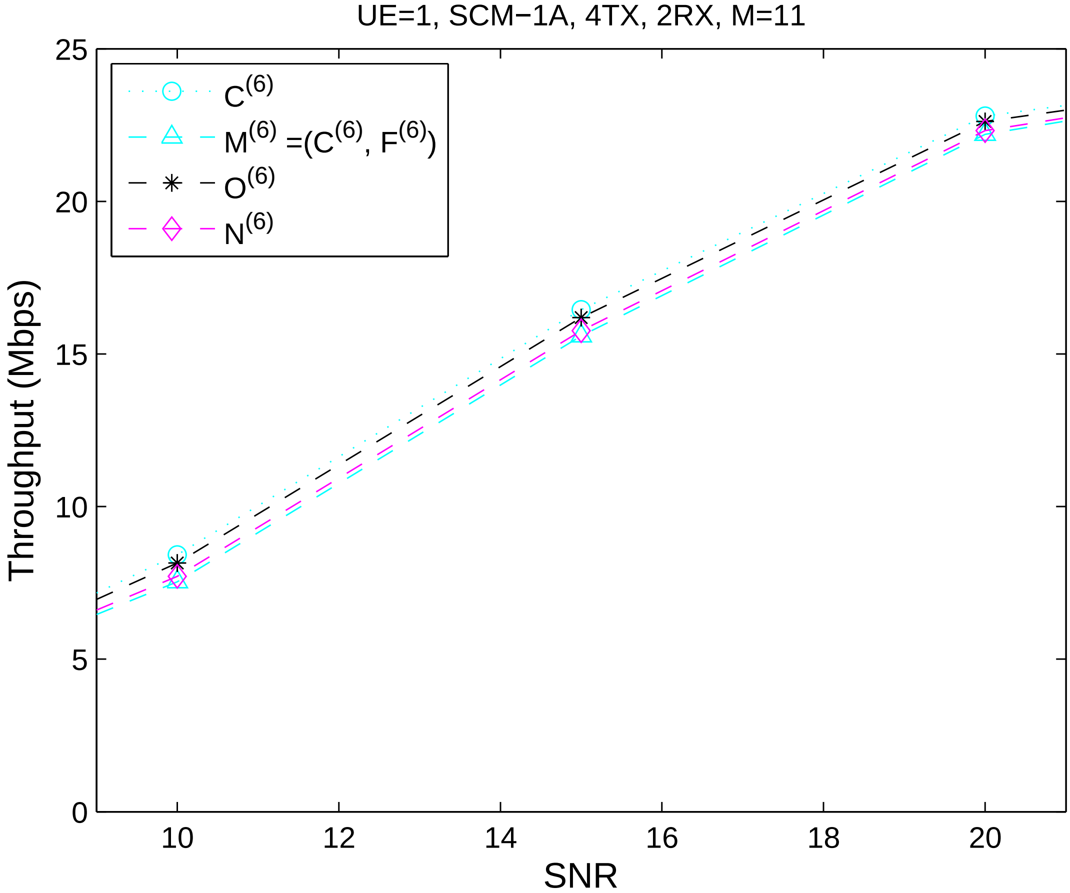

Figure 6: Link level throughput performance over M resource blocks.

6 Proposed Text

We propose the following text to be added to the Section 8.1, “IEEE 802.16m Air-Interface Protocol Structure” in SDD document under the heading “Transmit beamforming/precoding”

------------ Beginning of the text proposal ------------

8.1.x Multi-resolution Precoding Codebook

When the channel is correlated in time (or in frequency, e.g., across different tones in OFDM systems), the correlation can be used to considerably reduce the feedback requirement without loss in performance. The idea of multi-resolution codebook is to feedback only the variation in the channel, since typically quantizing the channel variations requires a smaller codebook than quantizing the channel itself. We propose the use of multi-resolution codebook for the DL transmission in IEEE802.16m. It is shown that for various number of codebook sizes, the precoding schemes based on the multi-resolution codebook considerably outperforms the ones based on the single-resolution codebook by using the same or reduced feedback load. Moreover, the complexity and memory requirement of such multi-resolution codebook precoding schemes is comparable with those of the conventional single-resolution codebook.

------------ End of the text proposal ------------