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Selective-MS Precoding for Downlink MIMO Transmissions

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1 Introduction

For 802.16m systems downlink MIMO techniques must be capable of providing spatial multiplexing (SM) and spatial diversity (SD) gains in the following radio environments:

- Macrocell
  - Rural Macrocell
  - Urban Macrocell
  - Suburban Macrocell
  - Bad Urban Macrocell
- Microcell
  - Urban Microcell
  - Bad Urban Microcell
- Picocell
  - Indoor Hot Spot
  - Indoor Small Office
  - Outdoor to Indoor

The particular downlink MIMO technique that may used depends mainly on BS/MS antenna configurations, MIMO channel conditions within a radio environment, and the availability and accuracy of channel state information (CSI).

In a macrocell BS antennas are typically above rooftops in order to support a large macrocell radius. Transmitted BS downlink signals may not be significantly scattered by channel obstacles since they are mainly below the transmit antennas. At the MS this may result in received signals with small angle-of-arrival spreads and low-rank MIMO channel matrices due to high antenna cross correlations (cross-polarized antennas may possibly be used to mitigate this problem). The low-rank channel matrices limit the possibilities for spatial multiplexing and spatial diversity. However, the small angle-or-arrival may allow the BS's transmitted signal energy to be focused to areas where one or more MSs are located (focused signal energy will also mitigate range problems for large macrocells).

In a macrocell MS mobility may be very high so accurate short-term CSI may not be available at a BS transmitter. Hence an open-loop MIMO technique may be more appropriate. Due to small angle-of-arrival spreads and the possibility of high MS mobility a fixed beamforming approach may be suitable for downlink MIMO transmissions.

In a microcell BS antennas are typically below rooftops so transmitted BS signals may be significantly scattered and faded by channel obstacles. At the MS this may result in large angle-of-arrival spreads and high or full rank MIMO channel matrices due to low antenna cross correlations. The full-rank channel matrices extend the possibilities for spatial multiplexing and spatial diversity. However, the large angular spreads at MSs make it more difficult to focus a BS's transmitted signal energy to specific areas where one or more MSs are located.

In a microcell MSs may be stationary, slowly moving, or within cars or public transportation vehicles. For stationary or slowly moving MSs accurate short-term CSI may be acquired by a BS in a TDD mode of operation. For stationary or slowly moving MSs a MIMO technique for SM gain or SD gain may be combined with linear precoding operation. Linear precoding may exploit the CSI available at the BS and be used to increase spectral efficiency and also help mitigate multi-user interference at the MSs.

For MSs in vehicles their mobility may be high so accurate short-term CSI may not be available at a BS. Hence an open-loop MIMO technique may be more appropriate for MSs within vehicles. Also, due to large angular spreads and the possibility of high MS mobility, a fixed beamforming approach with a set of fixed spatial sub-channels may not be appropriate for the downlink.

In a picocell BS antennas are typically low so transmitted BS signals will be significantly scattered and faded by channel obstacles. At an MS this typically results in large angle-of-arrival spreads and high or full rank MIMO channel matrices due to low antenna cross correlations. Similar to the microcell scenario, the full-rank channel matrices extend the possibilities for spatial multiplexing and spatial diversity. The large angular spreads make it more difficult for beamformer to focus a BS's transmitted signal energy to specific areas where one or more MSs are located.

In a picocell the coverage area is rather small and MSs are stationary or slowly moving. Hence accurate CSI may be acquired by a BS in a TDD mode of operation. The acquired CSI is also valid over larger time intervals. A MIMO technique for SM gain or SD gain may be combined with linear precoding operation to improve performance.

Indeed, the numerous radio environments for 802.16m systems motivates the usage of an adaptive MIMO system. BSs and MSs should be able to adaptively switch between DL MIMO techniques depending their antenna configurations and MIMO channel conditions within a radio environment. By switching between DL MIMO techniques an IEEE 802.16m system can dynamically optimize throughput or coverage for a specific radio environment.

To increase spectral efficiency and system throughput this contribution describes a downlink precoding technique that may be used in a microcell or picocell when MS mobility is low, channel matrices are of full rank, and accurate short-term CSI may be acquired by a BS. The proposed precoding technique is linear and may be combined with any other MIMO technique for SM gain or SD gain. It may provide a mode of operation for an adaptive MIMO system.

2 Open-loop Selective-MS Precoding

Space-time coding may be combined with linear precoding in order to increase spectral efficiency and throughput. Figure 1 shows a downlink system model that combines space-time coding and linear precoding. To describe the signals and the precoder design we use the following notation:

- N_T denotes the number of BS transmit antennas
- $N_{R,k} \geq 1$ denotes the number of receive antennas for the kth MS
- K_{active} denotes the number of active MSs serviced by the BS
- $N_R = \sum_{j=1}^{K_{active}} N_{R,j}$ denotes the total number of receive antennas distributed over all K_{active} MSs
- $M_{R,k} = N_R - N_{R,k}$ denotes the number of receive antennas for all MSs except the kth
- $N_{S,k} \leq \min(N_T, N_{R,k})$ denotes the number of independent spatial streams allocated to the kth MS
- $N_S = \sum_{j=1}^{K_{active}} N_{S,j}$ denotes the total number of independent spatial streams transmitted by the BS
- $\mathbf{W}_k$ denotes the N_T-by-$N_{S,k}$ linear precoding matrix for the kth MS

- $\mathbf{P}_k$ denotes the $N_{S,k}$-by-$N_{S,k}$ diagonal stream power loading matrix for the kth MS
- $\mathbf{s}_k$ denotes the $N_{S,k}$-by-1 data symbol vector for the kth MS
- $\mathbf{H}_k$ denotes the $N_{R,k}$-by-N_T matrix channel matrix for the kth MS. The (i, j)th element of $\mathbf{H}_k$ represents the channel gain and phase associated with the signal path from BS transmit antenna j to MS receive antenna i. Elements of $\mathbf{H}_k$ are modeled as independent complex Gaussian random variables with zero mean and unit variance. Channel matrices $\mathbf{H}_k$, $k = 1, 2, \ldots, K_{active}$, are of full rank and uncorrelated.
- $\mathbf{n}_k$ denotes the $N_{R,k}$-by-1 noise vector for the kth MS.

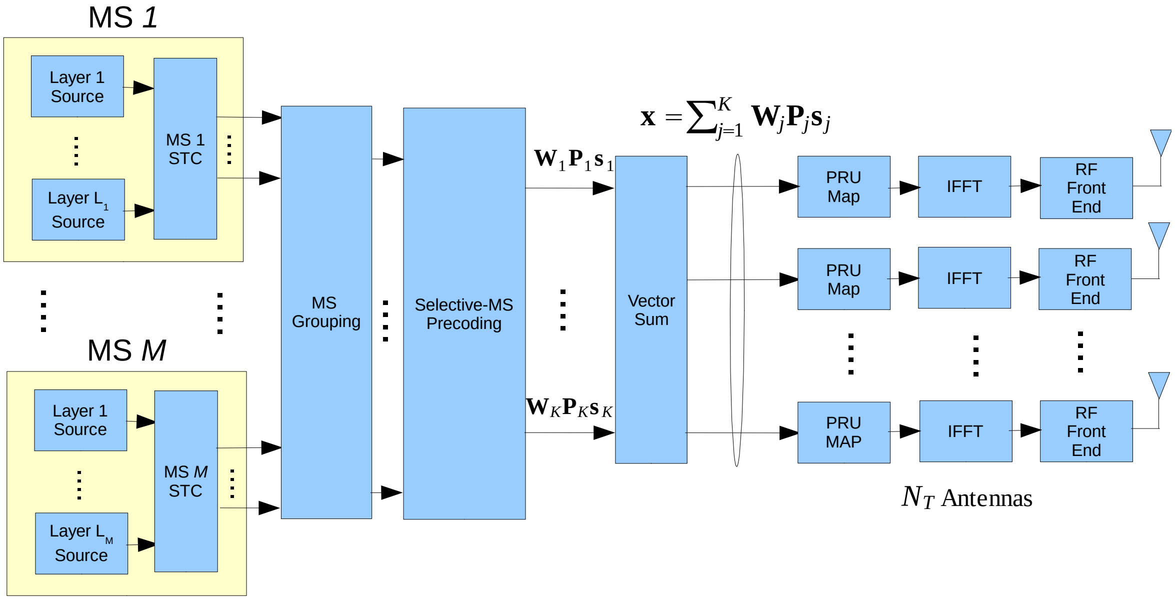

Figure 1: Conceptual block diagram of the precoding operation ($K = K_{active}$).

The signal transmitted by the BS is defined as the N_T-by-1 vector

$$\mathbf{x} = \sum_{j=1}^{K_{active}} \mathbf{W}_j \mathbf{P}_j \mathbf{s}_j \tag{1}$$

The received signal for the kth MS is the $N_{R,k}$-by-1 vector

$$\begin{aligned} \mathbf{y}_k &= \mathbf{H}_k \mathbf{x} + \mathbf{n}_k \\ &= \mathbf{H}_k \mathbf{W}_k \mathbf{P}_k \mathbf{s}_k + \mathbf{H}_k \sum_{j=1, j \neq k}^{K_{active}} \mathbf{W}_j \mathbf{P}_j \mathbf{s}_j + \mathbf{n}_k \end{aligned} \tag{2}$$

The first term on the right hand side is the desired signal for the kth MS. The second term is co-channel interference which can be eliminated if

$$\mathbf{H}_k \sum_{j=1, j \neq k}^{K_{active}} \mathbf{W}_j = \mathbf{0} \tag{3}$$

To eliminate co-channel interference we first construct the $M_{R,k}$-by-N_T matrix

$$\tilde{\mathbf{H}}_k = \begin{bmatrix}\mathbf{H}_1^T & \ldots & \mathbf{H}_{k-1}^T & \mathbf{H}_{k+1}^T & \ldots & \mathbf{H}_{K_{active}}^T\end{bmatrix}^T \tag{4}$$

and compute the singular value decomposition

$$\tilde{\mathbf{H}}_k = \tilde{\mathbf{U}}_k \tilde{\mathbf{\Sigma}}_k \tilde{\mathbf{V}}_k^H \tag{5}$$

Matrices $\tilde{\mathbf{U}}_k$ and $\tilde{\mathbf{V}}_k$ are $M_{R,k}$-by-$M_{R,k}$ and N_T-by-N_T unitary matrices. Matrix $\tilde{\mathbf{\Sigma}}_k$ is an $M_{R,k}$-by-N_T singular value matrix.

Given $\tilde{\mathbf{V}}_k$ the BS we construct the N_T-by-$(N_T - M_{R,k})$ matrix

$$\tilde{\mathbf{V}}_k^0 = \begin{bmatrix}\tilde{\mathbf{v}}_{k,M_{R,k}+1} & \ldots & \tilde{\mathbf{v}}_{k,N_T-1} & \tilde{\mathbf{v}}_{k,N_T}\end{bmatrix} \tag{6}$$

where the N_T-by-1 vector $\tilde{\mathbf{v}}_{k,i}$ denotes the ith column of $\tilde{\mathbf{V}}_k$. The orthonormal vectors within $\tilde{\mathbf{V}}_k^0$ form an orthonormal basis for the null space of $\tilde{\mathbf{H}}_k$ hence $\mathbf{H}_j \tilde{\mathbf{V}}_k^0 = \mathbf{0}$ for all $j \neq k$. Note however that $\tilde{\mathbf{V}}_k^0$ is non-unitary since it is not a square matrix.

A necessary condition for the N_T-by-$(N_T - M_{R,k})$ matrix $\tilde{\mathbf{V}}_k^0$ to exist is that

$$N_T > M_{R,k} \tag{7}$$

Similary, a necessary condition for all $\tilde{\mathbf{V}}_k^0$, $k = 1, 2, \ldots, K_{active}$, to exist is that

$$N_T > \max\left(M_{R,1}, M_{R,2}, \ldots, M_{R,K_{active}}\right) \tag{8}$$

Since $M_{R,k} = N_R - N_{R,k}$ and $N_{R,k} \geq 1$ the right hand side of the above inequality can be written as

$$\max\left(M_{R,1}, M_{R,2}, \ldots, M_{R,K_{active}}\right) = N_R - \min\left(N_{R,1}, N_{R,2}, \ldots, N_{R,K_{active}}\right) \tag{9}$$

Substitution then gives

$$N_T > N_R - \min\left(N_{R,1}, N_{R,2}, \ldots, N_{R,K_{active}}\right)$$

Hence the number of BS transmit antennas N_T must be as large as the *total* number of receive antennas N_R for all active MSs.

If the precoder matrix $\mathbf{W}_k$ is constructed from a linear combination of the orthonormal vectors within the N_T-by-$(N_T - M_{R,k})$ matrix $\tilde{\mathbf{V}}_k^0$ the equality $\mathbf{H}_k \mathbf{W}_j = \mathbf{0}$ will hold for all $j \neq k$. Let $\mathbf{C}_k$ denote an $(N_T - M_{R,k})$-by-$N_{S,k}$ coefficient matrix and define the N_T-by-$N_{S,k}$ precoder matrix as

$$\mathbf{W}_k = \tilde{\mathbf{V}}_k^0 \mathbf{C}_k = \begin{bmatrix}\tilde{\mathbf{V}}_k^0 \mathbf{c}_{k,1} & \tilde{\mathbf{V}}_k^0 \mathbf{c}_{k,2} & \ldots & \tilde{\mathbf{V}}_k^0 \mathbf{c}_{N_{S,k}}\end{bmatrix}$$

Here $\mathbf{c}_{k,j}$ denotes the jth column of $\mathbf{C}_k$. The jth column of $\mathbf{W}_k$ can be written as

$$\tilde{\mathbf{V}}_k^0 \mathbf{c}_{k,j} = c_{k,1j} \tilde{\mathbf{v}}_{k,M_{R,k}+1} + c_{k,2j} \tilde{\mathbf{v}}_{k,M_{R,k}+2} + \cdots + c_{k,N_T j} \tilde{\mathbf{v}}_{k,N_T}$$

where $c_{k,ij}$ denotes the ijth element in $\mathbf{C}_k$. In this form we see that each column of $\mathbf{W}_k$ is a linear combination of the orthonormal vectors within $\tilde{\mathbf{V}}_k^0$. Note also that $\mathbf{H}_k \mathbf{W}_j = \left(\mathbf{H}_k \tilde{\mathbf{V}}_j^0\right) \mathbf{C}_j = \mathbf{0}$ holds for any selection $\mathbf{C}_k$ and all $j \neq k$.

To eliminate the selection of elements $c_{k,ij}$ within $\mathbf{C}_k$ we set $N_T = N_R$ and $N_{R,k} = N_{S,k}$. These values satisfy the above condition $N_{S,k} \leq \min(N_T, N_{R,k})$ and the above condition for N_T. Using these values the column dimension of $\tilde{\mathbf{V}}_k^0$ becomes $N_T - M_{R,k} = N_{S,k}$ so $\tilde{\mathbf{V}}_k^0$ becomes an N_T-by-$N_{S,k}$ matrix and $\mathbf{C}_k$ an

$N_{S,k}$-by-$N_{S,k}$ matrix. Setting $\mathbf{C}_k$ to an $N_{S,k}$-by-$N_{S,k}$ identity matrix eliminates the selection of coefficients and the precoder matrix simplifies to the form

$$\mathbf{W}_k = \tilde{\mathbf{V}}_k^0 \tag{10}$$

The equality $\mathbf{H}_k\mathbf{W}_j = \mathbf{0}$ holds for all $j \neq k$ so the co-channel interference term will be eliminated and the received signal will be

$$\mathbf{y}_k = \mathbf{H}_k\mathbf{W}_k\mathbf{P}_k\mathbf{s}_k + \mathbf{n}_k \tag{11}$$

Note that for precoding we cannot use a common pilot for estimating the effective channel $\mathbf{H}_k\mathbf{W}_k\mathbf{P}_k$ since each MS uses a different precoding matrix $\mathbf{W}_k$ and possibly a different power scaling matrix.

The above precoding technique requires that the channels $\mathbf{H}_k$, $k = 1, 2, \ldots, K_{active}$, be available at the BS for all active MSs. This can be accomplished using MS-dedicated uplink pilot symbols that the BS may use to estimate $\mathbf{H}_k$. This open-loop approach exploits channel reciprocity and requires a TDD mode of operation. It also requires RF front-end calibration.

2.1 MS Grouping for Selective-MS Precoding

Selective-MS precoding will decrease the number of computations required for precoding and improve performance by better nulling the co-channel interference. In selective-MS precoding only a subset of the K_{active} active MSs is scheduled to receive DL subframe data. The selected subset is called an MS spatial group. We now describe how an MS spatial group may be formed.

A spatial MS grouping of active MSs is a set partition

$$\mathcal{G} = \{G_1, G_2, \ldots, G_{N_G}\} \tag{12}$$

where G_i denotes a MS spatial group and N_G the number of groups. Each MS spatial group G_i is a subset of the active MS set

$$\mathcal{M} = \{MS_1, MS_2, \ldots, MS_{K_{active}}\} = \bigcup_{i=1}^{N_G} G_i \tag{13}$$

where MS_i denotes the ith active MS. The total number of MS receive antennas N_R associated with a spatial group G_i must be less than or equal to N_T (i.e. $N_R \leq N_T$). The MS spatial groups are disjoint meaning their set intersections are null.

MSs within a group G_i will have uncorrelated channels $\mathbf{H}_k$. MSs with channel cross correlations $\mathbf{H}_k$ that are below a pre-defined threshold are placed in the same MS group. MSs that have highly correlated channels $\mathbf{H}_k$ are placed into different spatial MS groups. MSs belonging to the same group are assigned different precoding matrices $\mathbf{W}_k$. MSs within a spatial MS group can share the same physical layer resource units within a subframe. The larger an MS group the greater the gain in spectral efficiency and throughput. On the other hand, smaller MS groups allow the BS to transmit with higher average power per MS.

Finding the optimum MS grouping $\mathcal{G}$ requires a comparison between all possible MS groups. This is not practical so reduced complexity algorithms are required to find a sub-optimal MS grouping. Many sub-optimal MS grouping strategies are proposed in the literature.

3 Closed-loop Selective-MS Precoding

The above precoding technique requires that the channels $\mathbf{H}_k$, $k = 1, 2, \ldots, K_{active}$, be available at the BS for all active MSs. This can also be accomplished using a closed-loop approach where each MS-estimated

$\mathbf{H}_k$ is provided to the BS via an uplink signal. The closed-loop approach is applicable for both TDD and FDD modes of operation and channel reciprocity is not required.

A closed-loop feedback approach may be categorized as being analog or digital. Analog feedback typically refers to the case where non-quantized MS-estimated $\mathbf{H}_k$ are M-QAM modulated and then returned to the BS. Digital or quantized feedback typically refers to the case where the MSs make use of a vector quantization scheme and provides the BS with an encoded and modulated quantization index.

For the digital closed-loop approach it is simple to quantize MS-estimated channels $\mathbf{H}_k$ and transmit channel codebook indices that represent the quantized channels back to the BS. Another approach is quantization of the precoder $\mathbf{W}_k$ at the MS as opposed to the channel $\mathbf{H}_k$. However, this approach can not be used for the above described precoding technique since a computation for $\mathbf{W}_k$ requires that the kth MS have channel matrices $\mathbf{H}_j$ for all $j \neq k$. Moreover, even if an MS has these matrices the singular value decomposition described above may be too much for an MS to handle. It is easier for the BS to acquire these matrices and perform the computations for precoding described above.

We now describe how memoryless vector quantization (VQ) may be implemented and used for closed-loop precoding. Other applicable approaches are described in [4].

Memoryless vector quantization is a classification or encoding procedure which concerns the non-linear mapping of MS-estimated MIMO channel matrices $\mathbf{H}_k$ into bit vectors $\mathbf{b}_i$. The bit vectors label entries in a MIMO channel codebook $\mathcal{C}$ known by both the MSs and the BS. The bit vectors are determined by the MSs and are transmitted to a BS. The BS uses the received bit vectors to access a quantized MIMO channel matrix from the codebook $\mathcal{C}$.

More specifically, let

$$Q(\mathbf{H}_k) = \arg\min_{\mathbb{V}\in\mathcal{C}} S(\mathbf{H}_k, \mathbb{H}) = \arg\min_{\mathbb{V}\in\mathcal{C}} \left\| \mathbf{V}_k \mathbf{V}_k^H - \mathbb{V}\mathbb{V}^H \right\|_2 \tag{14}$$

denote an operation that maps $\mathbf{H}_k$ to its quantized representation $Q(\mathbf{H}_k)$. Note that for some matrix $\mathbf{A}$ the matrix norm operator $\|\mathbf{A}\|_2$ produces the largest singular value of $\mathbf{A}$. Some other functions that can be used for $S(\mathbf{H}_k, \mathbb{H})$ are defined within [4]. Jacobi rotations can be used to compute the singular value decomposition of the $N_{R,k}$-by-N_T matrix $\mathbf{H}_k$ to obtain $\mathbf{V}_k$. The matrix product $\mathbb{V}\mathbb{V}^H$ may be computed offline so a singular value decomposoition to find $\mathbb{V}$ is not needed. Matrices $\mathbb{V}_k\mathbb{V}_k^H$ and $\mathbb{V}\mathbb{V}^H$ are symmetric N_T-by-N_T matrices and N_T and $N_{R,k}$ are small (e.g. $N_T = 4$, $N_{R,k} = 2$) so the computations for $Q(\mathbf{H}_k)$ are practical MS computations.

Let the MIMO channel codebook be the K-dimensional set

$$\mathcal{C} = \left\{ \mathbb{V}_1 \quad \mathbb{V}_2 \quad \dots \quad \mathbb{V}_K \right\} \tag{15}$$

The channel codebook consists of right singular matrices $\mathbb{V}_i$, $i = 1, 2, \dots, K$, where each N_T-by-N_T matrix $\mathbb{V}_i$ is computed from the singular value decomposition $\mathbb{H}_i = \mathbb{U}_i \mathbb{D}_i \mathbb{V}_i^H$. Let

$$\mathbf{b}_k = f(Q(\mathbf{H}_k)) \tag{16}$$

denote an operation that maps a quantized MIMO channel $Q(\mathbf{H}_k)$ to length-$\lceil \log_2 K \rceil$ bit vector $\mathbf{b}_k$ within the MIMO channel index set

$$\mathcal{B} = \{\mathbf{b}_1, \mathbf{b}_2, \dots, \mathbf{b}_K\} \tag{17}$$

For example, $f(Q(\mathbf{H}_k))$ may be a simple look-up table operation that outputs a bit vector $\mathbf{b}_k$ given $Q(\mathbf{H}_k)$. When the BS receives $\mathbf{b}_k$ from the kth MS the BS uses $\mathbf{b}_k$ to read the corresponding MIMO channel stored in the codebook $\mathcal{C}$.

Codebook design can be performed in advance by using a set of MIMO channel training matrices obtained via simulations. Codebook design concerns the selection of a set of unitary matrices $\mathbb{V}_i$ that

Quantized MIMO Channel	3-bit Channel Index
$\mathbb{H}_1$	$\mathbf{b}_1 = 000$
$\mathbb{H}_2$	$\mathbf{b}_2 = 001$
$\mathbb{H}_3$	$\mathbf{b}_3 = 010$
$\mathbb{H}_4$	$\mathbf{b}_4 = 011$
$\mathbb{H}_5$	$\mathbf{b}_5 = 100$
$\mathbb{H}_6$	$\mathbf{b}_6 = 101$
$\mathbb{H}_7$	$\mathbf{b}_7 = 110$
$\mathbb{H}_8$	$\mathbf{b}_8 = 111$

Table 1: Example codebook entries and indices for closed-loop precoding

minimizes the mean of a quantizer distortion function. Since $\mathbb{V}_i$ is computed from a singular value decomposition of $\mathbb{H}_i$, the distortion function provides a measure of the difference between $\mathbf{H}_k$ and its quantized version $Q(\mathbf{H}_k)$.

Codebook design can be simplified via Grassmannian subspace packing. In this approach the objective is to find a set of unitary matrices $\mathbb{V}_i$, $i = 1, 2, \ldots, K$, such that the minimal subspace distance between the K matrices $\mathbb{V}_i$ is maximized. The following function can be used for this purpose

$$\max_{\mathcal{C}} \min_{\mathbb{V}_i, \mathbb{V}_j \in \mathcal{C}} \left\| \mathbb{V}_i \mathbb{V}_i^H - \mathbb{V}_j \mathbb{V}_j^H \right\|_2, \ i \neq j \tag{18}$$

Besides Grassmannian subspace packing other methods such as the Generalized Lloyd algorithm or a Monte Carlo method may be used. These are described in [4].

An example is given in Table 1, where we assume a codebook with $K = 8$ entries.

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5 Proposed Tex

Temporary SDD section numbers for the proposed text are in accordance with the current version of the SDD’s table of contents.

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11. Physical Layer

11.x Downlink MIMO

11.x.y. Downlink MIMO Adaptation

To provide spatial multiplexing (SM) and spatial diversity (SD) gains in numerous radio environments, BSs and MSs will be able to switch between DL MIMO techniques depending on downlink MIMO channel conditions. By switching between DL MIMO techniques an IEEE 802.16m system can dynamically optimize spectral efficiency and/or coverage for a specific radio environment.

11.x.y Downlink Precoding

Open- and closed-loop precoding techniques may be used to increase the spectral efficiency of downlink transmissions. Using precoding identical physical layer resource units (PRUs) may be used to transmit different downlink data. The identical PRUs may be concurrently transmitted to one or more MSs. Linear precoding may be combined with other MIMO techniques designed for SM gain or SD gain.

11.x.z Selective-MS Downlink Precoding

Open- and closed-loop selective-MS precoding are BS-centric precoding techniques that eliminate co-channel interference between MSs concurrently receiving downlink data. Since selective-MS precoding is base station centric it may also be used to facilitate BS-to-BS cooperation techniques for interference mitigation.

In selective-MS precoding a BS groups its active MSs into disjoint subsets called MS spatial groups. MSs within the same MS spatial group will have uncorrelated downlink MIMO channels. MSs that have highly correlated downlink MIMO channels will placed into different spatial MS groups. Different precoding matrices will be assigned to all MSs within an MS spatial group. MSs within a spatial MS group may share the same physical layer resource units (PRUs). The allocated PRUs may be concurenly transmitted thereby increasing downlink spectral efficiency. For each downlink subframe a BS scheduler will select which of the MS spatial groups will be allocated available PRUs.

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