Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**Closed Loop MIMO Precoding**
Date Submitted	**2004-11-04**
Source:	Erik Lindskog, Harold Artes, Djordje Tujkovic, Kamlesh Rath, V. Shashidhar, B. Sundar Rajan, Rahul Vaze, Andreas Bergkvist, Bob Lorenz, Babu Mandava, A. Paulraj, Aditya Agrawal Beceem Communications, Inc. 3930 Freedom Circle, Suite 101 Santa Clara, CA 95054 U.S.A. elindskog@beceem.com Voice: +1-408-387-5014
Re:	IEEE 802.16e D6 Draft
Abstract	To improve the closed loop MIMO
Purpose	To incorporate the changes here proposed into the 802.16e D4 draft.
Notice	
Release	
Patent Policy and Procedures	

Closed Loop MIMO Precoding

Erik Lindskog, Harold Artes, Djordje Tujkovic, Kamlesh Rath, V. Shashidhar, B. Sundar Rajan, Rahul Vaze, Andreas Bergkvist, Bob Lorenz, Babu Mandava, A. Paulraj, Aditya Agrawal

1 Introduction

Precoding for MIMO was introduced in IEEE802.16eD4. We here specify a mechanism for feedback of precoding information from the receiver to the transmitter and the precoding procedure.

1.1 Motivation

Precoding is aimed to exploit some channel information in order to improve performance. This channel information can be in various forms, and we focus on two types of information: long-term channel statistics and instantaneous channel estimates.

Channel statistics: The real world communication channels are usually not i.i.d. but have some underlying statistics, such as transmit antenna correlation and a non-zero mean (Ricean component). This information can be exploited by designing a precoder to enhance the system performance. Since the channel statistics change very slowly (on the order of seconds) this type of precoding will require very little feedback. Moreover, since the statistics are largely frequency independent when there is at most one dominant Ricean component statistics-based precoding is well suited for high-mobility users.

Instantaneous channel knowledge: Another form of channel information is the instantaneous channel estimate. If the channel estimates were accurate at the time of precoder use, this would be the only information needed for precoder design. However, there is a delay between the time when the channel is estimated and the time when the precoder based on this channel information is used. Even for low mobility users (above 5km/h) there is a substantial performance loss due to using delayed (outdated) chanel information. Indeed, as shown by simulation examples later on, from about 20km/h upwards there is even a loss due to using instantaneous-channel-knowledge-based precoding as compared to no precoding. This is true even if channel information is fed back once per frame.

Thus, we propose a precoding scheme that switches between a precoding matrix designed to work well when one chooses to rely on long-term channel properties, e.g. transmit antenna correlations and/or channel mean, and a precoding matrix designed to work well when the short term channel knowledge is relevant. The method includes definitions of how to set up the precoding feedback and information about when to switch from using the short term precoding matrix and the long term precoding matrix.

As stated above, we are not proposing using a per tone frequency selective precoding approach for long term precoding. For short-term precoding we deem a fully frequency selective approach to require too much feedback. We do however include the option to use per band short term precoders in band AMC operation. The above choices are motivated by the need to limit the amount of feedback as indicated by the example below.

<u>Example of feedback requirements</u>

Assume there are 256 active subscribers per sector that require feedback of long term precoding information. Assume the long term precoding information needs to be changed once per second. Our proposal requires two CQICH slots per long term feedback. This translates to an average of 2.5 CQICH slots per frame.

Assume there are 64 users per sector that can make use of short term feedback and that they have a fading rate of 5 Hz. These users may require a short feedback approximately once every 4 frames (assuming 1 frame is 5 ms and that there is a feedback delay of 10 ms). This requires about 16 CQICH slots per frame (approximately one OFDM symbol with 1024 subcarriers).

1.2 Codebook for Precoding Matrices

We restrict the precoding matrices, *W*, to be unitary matrices. The unitary precoding matrices are quantized according to a code book whose design is described here.

Let *L* denote the total number of entries in the codebook. Similar to [1], given a S x M_t matrix

$$U = [I\ U'],$$

M_t x M_t diagonal matrices

$$[C_k]_{m,m} = e^{\frac{j2\pi}{\sqrt[S]{L}}[U]_{k,m}}, k = 1,2,...,S; m = 1,...,M_t; C_k^{\sqrt[S]{L}} = I$$

and M_t x B matrix Y ($B<=M_t$), the entries in the codebook are given as

$$W_l = C_1^{l_1} C_2^{l_2} \ldots C_2^{l_S} Y ,$$

with $l = [l_1 \quad l_2 \ldots \quad l_S]$, and l_i are elements in the ring of integers mod $\sqrt[S]{\sqrt{L}}$. For simplicity, the basis matrix *Y* can be chosen as a selection of a total of *B* columns (set of indexes $\boldsymbol{B}_c$) of the *DFT* matrix

$$[DFT]_{m,b} = e^{j\frac{2\pi}{M_t}(m-1)(b-1)}, \qquad m,b = 1,...,M_t .$$

This enables more degrees of freedom for variety of feedback rates and better tuning of pre-coding to instantaneous and statistical channel information.

The criteria for the selection of a particular W_l at the receiver will depend on the given transmission scheme (A, B, C) and the type of detection algorithm. In the current simulations, we have set *S*=1. Also the number of entries in the codebook is always 64 irrespective of the rank of the pre-coding matrix, i.e., *L*=64 for *B*=1,2,3. This was chosen to assure that feedback for one pre-coding matrix requires only one CQICH channel. The matrices (vectors in this case of *S*=1) are chosen as in [2]. There is one 64 entry codebook for each precoding rank.

1.3 Short-Term Precoding

For short-term or instantaneous channel knowledge based precoding we propose to use eigenmode beamforming, i.e., transmitting energy into the direction of the strongest right singular vectors of the channel matrix . Since our codebook is designed using the theory of Grassmanian manifolds [1] a precoder only contains information about the subspace we would like to transmit energy to. Thus, we do not propose any weighting of the eigenmodes. Moreover, we define the number of spatial directions to be utilized by the precoder (rank of the precoder matrix) to be equal to the number of spatial streams. Thus, for spatial rate one we use standard beamforming. Let us denote the matrix product of precoding matrix and channel matrix as equivalent channel. Another way to view short-term precoding as suggeste here, is that we conduct spatial multiplexing on the equivalent channel. Ther is no need for a space-time diversity code here since the precoder will utilize all available diversity and array gain (assuming valid channel information).

1.4 Long-Term Precoding

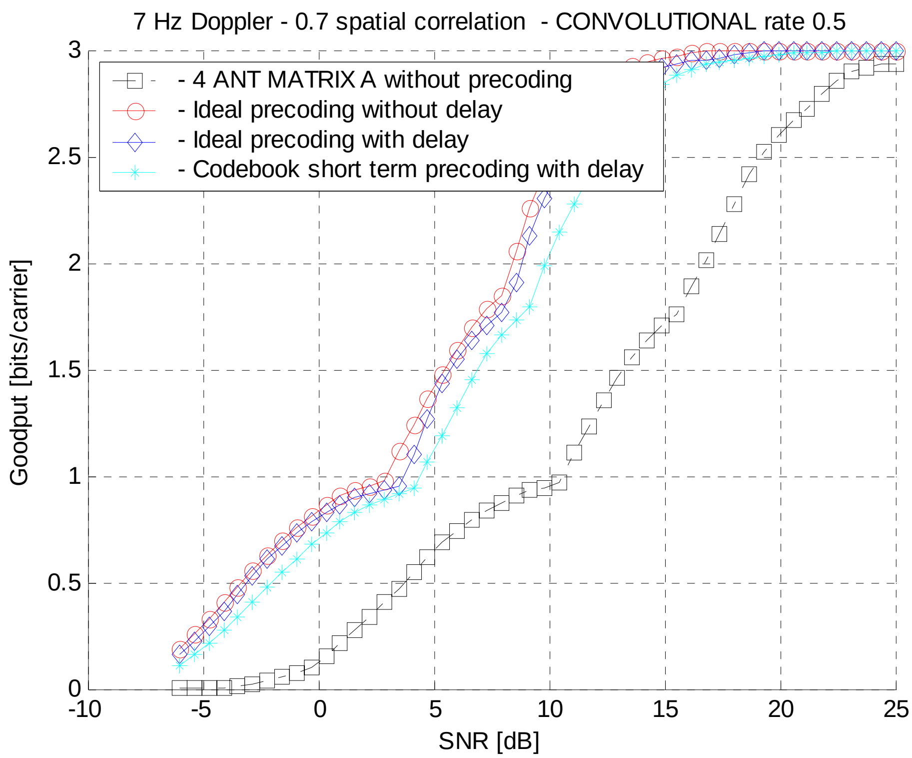
For long-term precoding our only available information is channel mean and covariance. Since this information is “less accurate” than instantaneous channel information, we do not know which spatial directions to beamform to. Thus for a given spatial rate, the first step is to decide how many spatial directions we have to transmit to based on the channel statistics. The number of spatial directions equals the rank of the precoder matrix and also the number of virtual transmit antennas of the equivalent channel. As an example consider spatial rate one. If, in the absence of any channel mean, the transmit covariance matrix of the channel is rank one we simply use a rank one beamformer leading to an equivalent SISO channel. If the transmit covariance matrix would contain two dominant eigenvalues we would use a rank two precoding matrix leading to two virtual transmit antennas. Here, we must use a space-time diversity code to optimally distribute our single spatial data stream to both available virtual antennas (spatial transmit directions).
In general if the number of spatial directions we decide to transmit to (based on the statistical information) is greater than the spatial rate we must use the appropriate space-time diversity code from the standards document to bridge the spatial streams to the virtual transmit antennas.

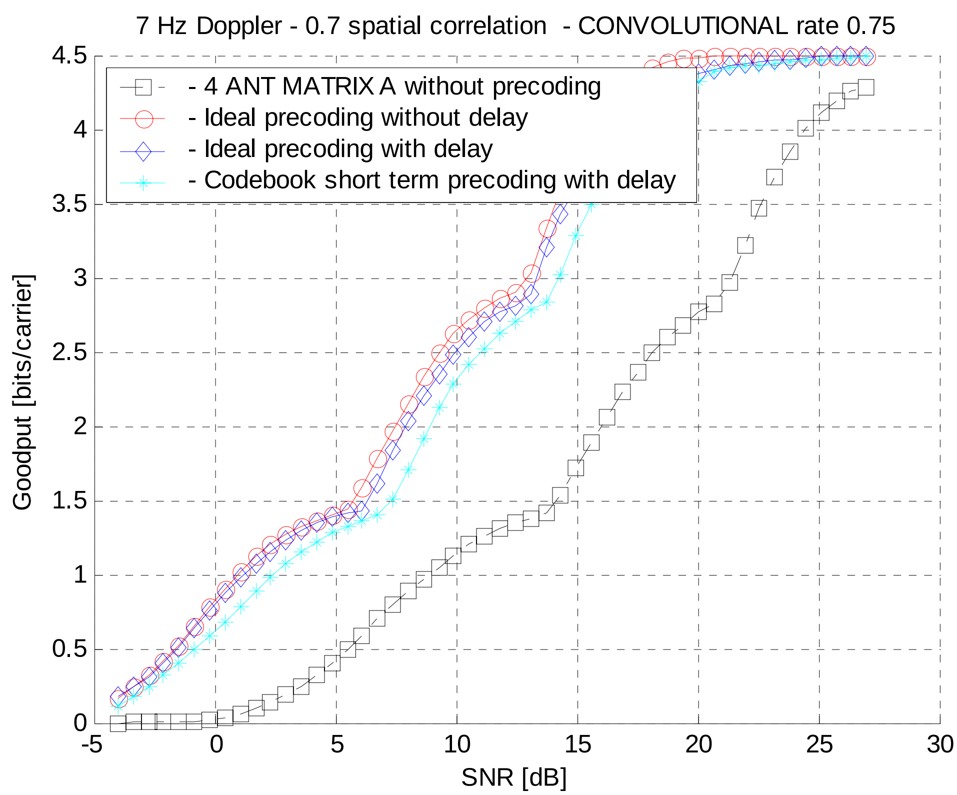
Example1: For SCM channel model with 4 lambda antenna spacing, 2 degrees Laplacian angular spread, 4 antennas makes a total width of ~1.5 m for a 2.5 GHz system. Spatial correlation between adjacent antennas becomes 0.8624 (see Reference [3])

Example2: For SUI Channel models [4] , large K-factors are quite frequent, e.g. SUI-1 has 11dB (90% cell coverage, 30 degree antenna) while for SUI-2, the K factor is 8dB.

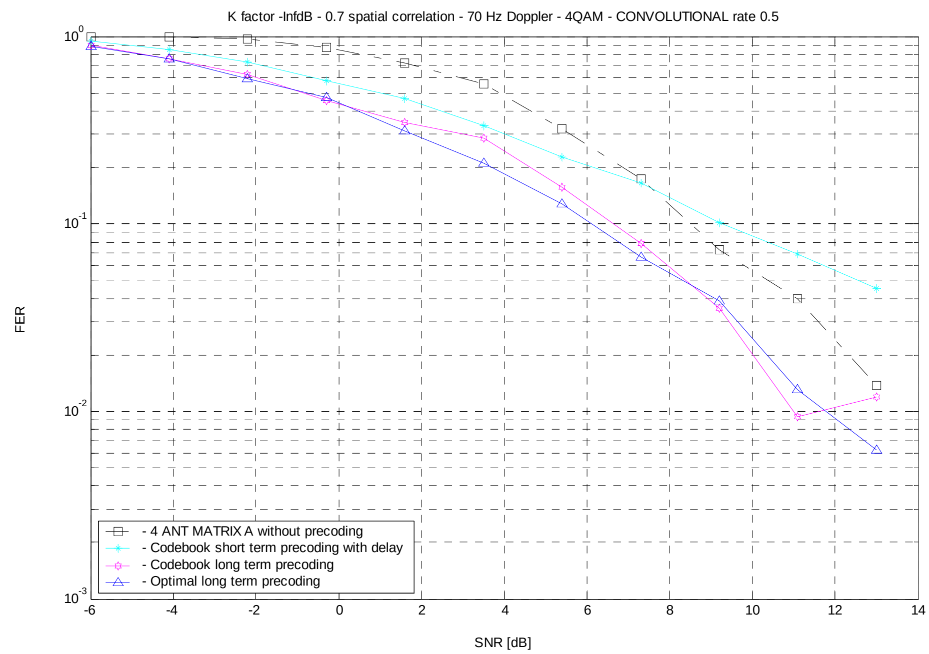
1.5 Simulation results

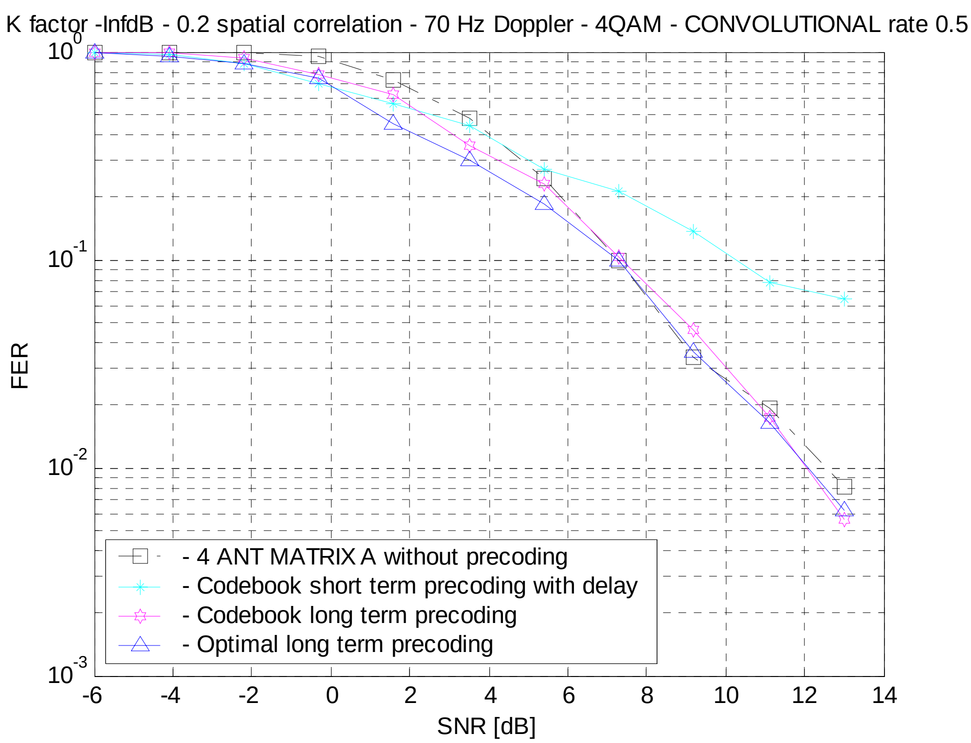
The following two figures show short term precoding gain of 6dB and 7db at a goodput of 2 bit/carrier with 4,16 and 64 QAM and 2 frames delay


7 Hz Doppler - 0.7 spatial correlation - CONVOLUTIONAL rate 0.5
- 4 ANT MATRIX A without precoding
- Ideal precoding without delay
- Ideal precoding with delay
- Codebook short term precoding with delay
Goodput [bits/carrier]
SNR [dB]

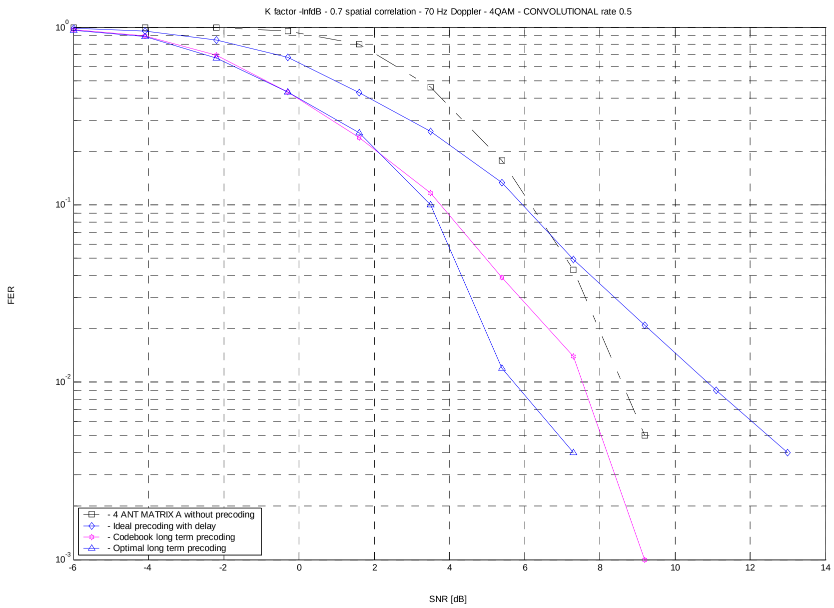

7 Hz Doppler - 0.7 spatial correlation - CONVOLUTIONAL rate 0.75
- 4 ANT MATRIX A without precoding
- Ideal precoding without delay
- Ideal precoding with delay
- Codebook short term precoding with delay
Goodput [bits/carrier]
SNR [dB]

The following plots show long term precoding gains for different spatial correlations and Ricean K factors. Significant gains are achieved whenever there is a spatial correlation or K factor. It can be observed that instantaneous precoding yields inferior performance compared to open loop Tx diversity results due to high Doppler. Even with no spatial correlation and K-factor, long term precoding is not worse than open loop diversity.





The figure below shows long term coding gains in diversity allocation over frequency selective channel using single frequency independent precoder for the whole band.



2 Specific text changes

---------Start text proposal-------

[Modify the following Table 298a in section 8.4.5.3.12.1]

Table 298a. CQICH Enhanced allocation IE format

Syntax	Size (bits)	Notes
CQICH_Enhanced_Alloc_IE() {		
Extended DIUC	4	0x09
Length	4	Length in bytes of following fields
CQICH_ID	variable	Index to uniquely identify the CQICH resource assigned to the MSS
Period (=p)	2	A CQI feedback is transmitted on the CQICH every 2^p frames
Frame offset	3	The MSS starts reporting at the frame of which the number has the same 3 LSB as the specified frame offset. If the current frame is specified, the MSS should start reporting in 8 frames
Duration (=d)	3	A CQI feedback is transmitted on the CQI channels indexed by the CQICH_ID for 10 x 2^d frames. If d== 0, the CQICH is de-allocated. If d == 111, the MSS should report until the BS command for the MSS to stop.
N_T actual BS antennas	3	001 = Reserved

		010 = 2 actual antennas 011 = 3 actual antennas 100 = 4 actual antennas 101 = 5 actual antennas 110 = 6 actual antennas 111 = ~~7~~ 8 actual antennas 000 = ~~8~~ 12 actual antennas
Feedback_type	2	00 = Fast DL measurement 01 = ~~MIMO Antenna Feedback~~ Indices to precoding matrix in code book. 10 = MIMO mode and permutation zone feedback 11 = Feedback of life span of the short term precoding matrix, rank of code book and index for long term precoding matrix in code book.
CQICH_Num	4	Number of CQICHs assigned to this CQICH_ID is (CQICH_Num +1)
for (i=0;i<CQICH_Num;i++) {		
Allocation index	6	Index to the fast feedback channel region marked by UIUC=0
}		
if (Feedback_type ~~!~~= ~~0100~~10) { MIMO_permutation_feedback cycle }	2	00 = No MIMO and permutation mode feedback 01 = the MIMO and permutation mode indication shall be transmitted on the CQICH indexed by the CQICH_ID every 4 frames. The first indication is sent on the 8th CQICH frame. 10 = the MIMO mode and permutation mode indication shall be transmitted on the CQICH indexed by the CQICH_ID every 8 frames. The first indication is sent on the 8th CQICH frame. 11 = the MIMO mode and permutation mode indication shall be transmitted on the CQICH indexed by the CQICH_ID every 16 frames. The first indication is sent on the 16th CQICH frame.
if (Feedback_type = 01) { Nr CQICH for feedback of index for short term precoding matrix}	2	Nr CQICH for feedback of an equal number of indices for short term precoding matrix. (To enable feedback of multiple precoders in the case of band AMC operation.)
if (Feedback_type = 01) { Switch for choice of common or distinc precoding matrices for each band in band AMC mode}	1	00 = One common precoder for all bands. 01 = Distinct precoders for the bands with the highest S/N values, up to the number of short term precoders fed back. Six bits for each short term code book index. 10 = . Distinct precoders for the bands with the highest S/N values, up to the number of short term precoders fed back. Six bits for the precoding matrix for the band with the highest S/N and three bits for the remaining precoding matrices. 11 = Reserved.
if (Feedback_type = 01) { Feedback cycle for feedback of	4	0000 = Feed back one index every frame. 0001 = Feed back one index 2nd frame.

index for short term precoding matrix}		0010 = Feed back one index 3rd frame. 0011 = Feed back one index 4th frame. 0100 = Feed back one index 6th frame. 0101 = Feed back one index 8th frame. 0110 = Feed back one index 10th frame. 0111 = Feed back one index 12th frame. 1000 = Feed back one index 16th frame. 1001 = Feed back one index 20th frame. 1010 = Feed back one index 24th frame. 1011 = Feed back one index 32nd frame. 1100 = Feed back one index 40th frame. 1101 = Feed back one index 48th frame. 1110 = Feed back one index 56th frame. 1111 = Feed back one index 64th frame.
if (Feedback_type = 10) { Feedback cycle for feedback of life span of short term precoding matrix, rank of code book for long term precoding matrix and feedback of long term precoding matrix}	3	000 = Feed back every 16th frame. 001 = Feed back every 32nd frame. 010 = Feed back every 64th frame. 011 = Feed back every 128th frame. 100 = Feed back every 256th frame. 101 = Feed back every 512th frame. 110 = Feed back every 1024th frame. 111 = Feed back every 2048th frame.
if (Feedback_type = 10) { Precoding feedback delay}	2	00 = 0 frames feedback delay. 01 = 1 frame feedback delay. 10 = 2 frames feedback delay. 11 = 3 frames feedback delay.
Padding	*variable*	The padding bits are used to ensure the IE size is integer number of bytes.

[Add the following text into section 8.4.8.3.6]

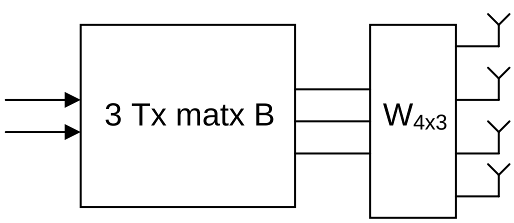
MIMO Precoding Method and Feedback

The BS can set up CQICH feedback of the life span, $\Delta\tau$, in number of frames, of the short term precoding matrix, W_{ST}, rank of code book for long term precoding matrix and index in this code book to the long term precoding matrix, W_{LT}. The setup of this CQICH feedback is specified in the CQICH Enhanced allocation IE format in Table 298a. When there is no feedback of the index to the short term precoding matrix, then there should be no feedback of the life span of the short term precoding matrix.

The rank of the code book determines the set from which the space-time code matrices are being chosen. If the rank of the code book is 3, then the space-time code matrices to choose from is the set of space-time code matrices for 3 Tx antennas.

Clarifying example:

> Assume a system with 4 transmit antennas and codebook with rank 3, i.e., the matrices in the codebook have 4 rows and 3 columns. Further assume that spatial rate 2 was chosen, then the space-time code matrix B (designed for spatial rate two and 3 Tx antennas) is applied to distribute the two spatial data streams to the three columns of the precoding matrix. The precoding matrix will subsequently direct the energy applied to each column to one spatial direction (transmitted from all four antennas) each.



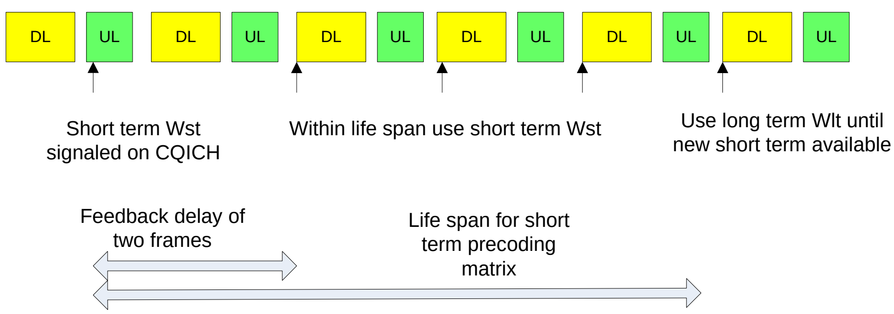
The following table specifies all the applicable cases.

Rate	Short term pre-coding (instantaneous CSI)	Long term pre-coding (based on channel statistics) a) rank 1, b) rank 2, c) rank 3, d) rank 4
1	SISO+BF(rank1 W_{4x1})	a) SISO+W_{4x1}, b) 2 Tx matx A+W_{4x2}, c) 3Tx matx A+W_{4x3}, d) 4Tx1 matx A+W_{4x4} (W_{4x4}=I, i.e., no pre-coding)
2	2 Tx SM+EigBF(rank 2 W_{4x2})	a) NA b) 2 Tx SM+W_{4x2}, c) 3Tx2 matx B+W_{4x3}, d) 4Tx2 matx B+I

The BS can also set up CQICH feedback of an index in a code book to the short term precoding matrix, W_{ST}. The setup of this CQICH feedback is specified in the CQICH Enhanced allocation IE format in Table 298a.

When the SS feeds back a short term precoding matrix, W_{ST} , the BS should precode the data transmitted to the SS using W_{ST} . The precoding with this precoding matrix should start after the precoding feedback delay specified by the BS in the setup of the CQICH feedback for the long term precoding feedback.

Beyond the life span of the short term precoding matrix, the BS should precode the data transmitted to the SS with the long term precoding matrix until the next short term precoding matrix is available to be used. The mechanism is illustrated in the following picture.



For band AMC the BS has the choice to request a common precoding matrix for all bands or can request a programmable number, N, of precoding matrices to be fed back for the N best bands in an ordered fashion. In the latter case, the precoding matrices are associated with the bands with the highest S/N values. As a secondary selection criteria, in case the bands with the highest S/N are not unique, the bands with the lowest band index are chosen first. The code book indices for the precoding matrices are ordered in increasing band index order. If the base station chooses to use a band for which a short term precoder is not fed back, the BS shall use the long term precoding matrix if such a precoding matrix is available.

As an option, the precoders for the different bands can be quantized with 6 bits for the band with the highest S/N and with 3 bits for the precoders for the remaining bands.

The mapping of the feedback of the index in the code book for the short term precoding matrix is described in Table V. The mapping of the feedback of the life span of the short term precoding matrix, the rank of the code book for the long term precoding matrix and the index in the code book for the long term precoding matrix is described in Tables W, X and Y.

CQICH number	**Field definition**	**Field content**
CQICH 0	Bits 0-5	Index in code book for short term precoding matrix.

Table V: Information mapping for CQICH channels for feedback of index in code book for short term precoding matrix. In the case multiple short term precoding matrices are used in band AMC mode, the additional code book indices for the additional short term precoding matrices are fed back on CQICH number 1-3. These precoders are associated with the bands for which the S/N values are the highest. As a secondary selection criteria, in case the bands with the highest S/N are not unique, the bands with the lowest band index are chosen first. They are ordered in increasing band index order.

CQICH number	**Field definition**	**Field content**
CQICH 0	Field 1: Bits 0-3	Life span of short term precoding matrix. See Table X.
	Field 2: Bits 4-5	Rank of code book for long term precoding matrix. See Table Y.
CQICH 1	Bits 0-5	Index in code book for long term precoding matrix

Table W: Information mapping for CQICH channels for feedback of life span of short term precoding matrix, rank of code book for long term precoding matrix and index in code book for long term precoding matrix.

Bit field	**Life span in number of frames**
0000	1
0001	2
0010	3
0011	4
0100	6
0101	8
0110	10
0111	12
1000	16
1001	20
1010	24
1011	32
1100	40
1101	48
1110	56
1111	64

Table X: Message format and interpretation for feedback of life span of short term precoding matrix.

Bit Field	Rank of code book for long term precoding matrix
00	1
01	2
10	3
11	4

Table Y: Message format and interpretation for feedback of rank of code book for long term precoding matrix.

---------End text proposal-------

References

[1] B. Hochwald et al, “Systematic Design of Unitary Space-Time Constellations”, IEEE Transactions on Information Theory, Vol 46, No 6, pp1962-1973, Sept 2000

[2] Closed loop MIMO precoding with limited feedback, C. Zhang et. al, C80216e_262r1.

[3] 3GPP/3GPP2 SCM-135, SCM v7.0, 3GPP document TR25.996

[4] Channel Models for Wireless Applications, Erceg et. al. C80216-3c-01_29r5