Document made available under the Patent Cooperation Treaty (PCT)

International application number: PCT/CA05/001474

International filing date: 29 September 2005 (29.09.2005)

Document type: Certified copy of priority document

Document details:
Country/Office: US
Number: 60/614,621
Filing date: 30 September 2004 (30.09.2004)

Date of receipt at the International Bureau: 01 November 2005 (01.11.2005)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

CA05/1474

PA 1338279

THE UNITED STATES OF AMERICA

TO ALL TO WHOM THESE PRESENTS SHALL COME:

UNITED STATES DEPARTMENT OF COMMERCE

United States Patent and Trademark Office

June 28, 2005

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE UNDER 35 USC 111.

APPLICATION NUMBER: ***60/614,621***
FILING DATE: ***September 30, 2004***

By Authority of the
Under Secretary of Commerce for Intellectual Property
and Director of the United States Patent and Trademark Office

M. Tarver

M. TARVER
Certifying Officer

PTO/SB/16 (09-04)
Approved for use through 07/31/2006. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE
Under the Paperwork Reduction Act of 1995, no persons are required to respond to a collection of information unless it displays a valid OMB control number.

22651 U.S.PTO

22154 U.S.PTO
60/614621
093004

PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No. EV517424492US

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
MING	JIA	OTTAWA, ONTARIO, CANADA

Additional inventors are being named on the ONE *separately numbered sheets attached hereto*

TITLE OF THE INVENTION (500 characters max):

METHODS AND APPARATUS OF CLOSED LOOP MIMO PRE-CODING AND FEEDBACK FOR IEEE802.16e

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

☑ The address corresponding to Customer Number: 00626

OR

☐ Firm or Individual Name

Address		
City	State	Zip
Country	Telephone	Fax

ENCLOSED APPLICATION PARTS *(check all that apply)*

☑ Specification *Number of Pages* 15

☑ Drawing(s) *Number of Sheets* 69

☐ Application Data Sheet. See 37 CFR 1.76

☐ CD(s), Number of CDs

☐ Other (specify)

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☐ Applicant claims small entity status. See 37 CFR 1.27.

☐ A check or money order is enclosed to cover the filing fees.

☐ Payment by credit card. Form PTO-2038 is attached.

☑ The Director is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number: 14-1315
A duplicative copy of this form is enclosed for fee processing.

FILING FEE Amount ($) 160.00

☐ The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government. No.

☐ Yes, the name of the U.S. Government agency and the Government contract number are:

SIGNATURE

Date September 30, 2004

TYPED or PRINTED NAME PAUL C. HASHIM

REGISTRATION NO. 31,618
(if appropriate)

TELEPHONE 972-684-7886

Docket Number: 17381ROUS01P

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

This collection of information is required by 37 CFR 1.51. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 8 hours to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.

If you need assistance in completing the form, call 1-800-PTO-9199 and select option 2.

PROVISIONAL APPLICATION COVER SHEET
Additional Page

PTO/SB/16 (09-04)
Approved for use through 07/31/2006. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

First Named Inventor	MING JIA	Docket Number	17381ROUS01P

INVENTOR(S)/APPLICANT(S)

Given Name (first and middle [if any])	Family or Surname	Residence (City and either State or Foreign Country)
WEN	TONG	OTTAWA, ONTARIO, CANADA
PEIYING	ZHU	KANATA, ONTARIO, CANADA

Number ONE of ONE

WARNING: Information on this form may become public. Credit card information should not be included on this form. Provide credit card information and authorization on PTO-2038.

PROVISIONAL PATENT APPLICATION

SUBMITTED ON SEPTEMBER 30, 2004

TITLE:

SYSTEM AND METHOD FOR CLOSED LOOP MIMO PRE-CODING AND FEEDBACK

INVENTORS:

MING JIA, OTTAWA, ONTARIO CANADA

WEN TONG, OTTAWA, ONTARIO CANADA

PEIYING ZHU, KANATA, ONTARIO CANADA

SYSTEM AND METHOD FOR CLOSED LOOP MIMO PRE-CODING AND FEEDBACK

The present invention generally relates to closed loop MIMO (Multiple Input Multiple Output) pre-coding and feedback, and more specifically to closed loop MIMO pre-coding and feedback for purposes of the IEEE 802.16(e) and IEEE 802.11(n) standards.

BACKGROUND OF THE INVENTION

As will be apparent to one of skill in the art there are numerous problems with the current IEEE 802.16(e) standard that need to be resolved including:

[1] MIMO channel feedback bandwidth reduction
[2] Antenna group selection
[3] MIMO channel feedback ageing
[4] Vector quantization for the MIMO channel
[5] MIMO feedback flow control associated MAC design
[6] Feedback channel design
[7] Feedback STC coding and channel sounding

While several solutions have been proposed in IEEE802.16(e) and IEEE802.11(n) for the closed loop MIMO pre-coding transmission, they are not practical for the following reasons:

[1] The Hausholder transform based SVD beam former feedback: The problem with this approach is that it is too complex for mobile channel realization

[2] Single user based fixed sub-channel allocation: The problem with this approach is that it has 2~3 times capacity loss compared to multi-user diversity

[3] Receiver based vector channel quantization: The problem with this approach is that it exponentially increases terminal complexity

A need exists therefore for an improved system and method for enabling closed loop MIMO pre-coding and feedback.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a closed loop MIMO pre-coding and feedback system and method for the IEEE802.16(e) and IEEE 802.11(n) standards.

It is another object of the invention to provide a closed loop MIMO pre-coding and feedback system and method for the WiMAX forum.

It is another object of the invention to provide a multi-user allocation for an OFDMA banded sub-channel

It is another object of the invention to provide feedback ageing processing

It is another object of the invention to provide differential feedback of a MIMO channel

It is another object of the invention to provide Givens-rotation based decomposition of a beam-former

It is another object of the invention to provide a multi-user scheduled downlink (DL) MIMO transmission

It is another object of the invention to provide MAC control of MIMO feedback

It is another object of the invention to provide a space time coded MIMO feedback channel

It is another object of the invention to provide combined sounding of a MIMO channel and CQI (channel quality indicator) feedback

It is another object of the invention to provide first multi-user feedback of a MIMO channel to a basestation (BTS) by MIMO channel compression or uplink (UL) MIMO channel sounding

It is another object of the invention to provide a Multi-user selection and allocation strategy

It is another object of the invention to provide multi-user pre-coding transmission to increase the range or to separate the inter-user interference.

DETAILED DESCRIPTION OF THE INVENTION

The following provides a glossary of the terms used in this application:

AMC	Adaptive Coding and Modulation
BS or BTS	Base Station
CL_MIMO	Closed Loop MIMO
CQI	Channel Quality Indicator
CQICH	CQI channel
DFT	Discrete Fourier Transform
FB	Feedback
FDD	Frequency Duplex
FFT	Fast Fourier Transform
MIMO	Multiple Input Multiple Output
MLD	Maximum Likelihood Detector
MSE	Minimum square error
MSS	Mobile Subscriber Station
PUSC	Partially Utilized Sub-Channel
QoS	Quality of service
SISO	Single Input Single Output
SVD	Singular Value Decomposition
STTD	Space Time Transmit Diversity
SM	Spatial Multiplexing
SQ	Scalar Quantize
TDD	Time Duplex
VQ	Vector Quantize

The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the invention and illustrate the best mode of practicing the invention. Upon reading the following description in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the invention and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

In accordance with a broad embodiment of the invention there is provided a way of facilitating closed loop MIMO pre-coding and feedback in a communications network operating in accordance with the IEEE 802.16(e) and IEEE 802.11(n) standards.

Prior to describing the details, however, a brief overview of an IEEE 802.16(e) / IEEE 802.11(n) environment in accordance with a broad embodiment of the invention is presented in **Figure 1**. As will be apparent to one of skill in the art the various boxes depicted therein are representative of algorithms which may be embedded in software, firmware or an ASIC (application specific integrated circuit). The broader inventions are not intended to be limited in this regard.

As shown in Figure 1 particular embodiments of the invention can be largely grouped into four categories of algorithms for purposes of illustration:

- Multi-User Selection (Embodiment 1.0): includes algorithms for organizing users, organizing antennas and selecting sub-bands;
- Quantized MIMO Channel Feedback (Embodiment Group 2.0): includes algorithms for facilitating feedback from a terminal to a BTS;
- MAC Layer (Embodiment 3.0): includes algorithms for the overall operation of the IEEE 802.16(e) or 802.11(n) environment
- Feedback channel for MIMO channel information MIMO (Embodiment 4.0): includes the feedback channel structure with the channel sounding capability and space time coding on the feedback channel.

In accordance with an embodiment of the invention Embodiments 1.0 and 3.0 occurs predominately within an associated BTS, Embodiment 2.0 predominately within an associated terminal, and Embodiment 4.0 occurring in both.

Regarding the sub-Embodiments of Embodiment 2.0 (2.1 and 2.2) one of skill in the art will appreciate that these algorithms are generally alternative to each other and need not co-exist. Similarly their respective sub-Embodiments are alternatives and need not co-exist.

In accordance with an embodiment of the invention the sub-Embodiments of Embodiment 4.0 co-exist.

Figures 2 and **3** present a comparison of SVD to Antenna Grouping for purposes of providing context for Embodiment 1.0.

Figure 4 presents an antennal grouping algorithm in accordance with an embodiment of the invention (Embodiment 1.0.1 – Modes Selection)

Figure 5 presents an antenna grouping algorithm in accordance with an embodiment of the invention (Embodiment 1.0.2 – Antenna Grouping Criterion)

Figure 6 presents an antenna grouping algorithm in accordance with an embodiment of the invention (Embodiment 1.0.3 – Antenna Group Selection)

Figure 6A presents a multi-user pre-coding algorithm in accordance with an embodiment of the invention (Embodiment 1.1.0 – Dirty Paper coding)

Figure 6B presents a multi-user pre-coding algorithm in accordance with an embodiment of the invention (Embodiment 1.1.1 – Multi-User Pre-coding with assigned set of users)

Figure 6C presents a multi-user pre-coding algorithm in accordance with an embodiment of the invention (Embodiment 1.1.2 – Multi-User Pre-coding with multi-user diversity)

Note, the designations 6A through 6C were chosen in the interests of time and does not necessarily suggest a relationship with Figure 6 or each other.

Figure 7 presents a direct differential encoding algorithm in accordance with an embodiment of the invention (Embodiment 2.1.1.0 – Architecture (1))

Figure 8 presents a direct differential encoding algorithm in accordance with another embodiment of the invention (Embodiment 2.1.1.0 – Architecture (2))
Figure 9 presents a direct differential encoding algorithm (FB) in accordance with an embodiment of the invention (Embodiment 2.1.1.1 – Differential Encoder: 1 bit DPCM)

Figure 10 presents a direct differential encoding algorithm (FB) in accordance with an embodiment of the invention (Embodiment 2.1.1.2 – Differential Encoder: 1 bit Delta / Sigma)

Figure 11 presents a direct differential encoding algorithm (FB) in accordance with an embodiment of the invention (Embodiment 2.1.1.2 – Differential Encoder: 1 bit Delta / Sigma)

Figure 12 presents a direct differential encoding algorithm (FB) in accordance with an embodiment of the invention (Embodiment 2.1.1.3 – Differential Encoder Operation)

Figure 13 presents a direct differential encoding algorithm (FB) in accordance with an embodiment of the invention (Embodiment 2.1.1.4 – Feedback Channel)

Figure 14 presents a differential encoding of transformed MIMO channel algorithm in accordance with an embodiment of the invention (Embodiment 2.1.2.1 – Differential encoding of unitary matrix)

Figure 15 presents a differential encoding of transformed MIMO channel algorithm in accordance with an embodiment of the invention (Embodiment 2.1.2.2 – Differential encoding of vector weights)

Figure 16 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.1.0 – Givens Rotation Architecture)

Figure 17 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.1.1 – Givens Rotation for 2-Transmit Antenna)

Figure 18 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.1.2 – Givens Rotation for 3-Transmit Antenna)

Figure 19 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.1.3 – Givens Rotation Architecture for 4-Transmit Antenna)

Figure 20 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.1.4 – Givens Rotation Architecture for n-Transmit Antenna)

Figure 21 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.1.5 – Truncation of Givens Expansion)
Figure 22 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.1.6 – Truncation of Givens Expansion)

Figure 23 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.1.7 – Bit Allocation (1))

Figure 24 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.1.7 – Bit Allocation (2))

Figure 25 presents an SVD based Givens transform SQ algorithm in accordance with an embodiment of the invention (Feedback requirement Example)

Figure 26 presents an SVD based Givens transform VQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.2.1 – Grassmann Subspace Packing)

Figure 27 presents an SVD based Givens transform VQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.2.2 – Spherical Code Based Quantizer (1))

Figure 28 presents an SVD based Givens transform VQ algorithm in accordance with an embodiment of the invention (Embodiment 2.2.2.3 – Spherical Code Based Quantizer (2))

Figure 29 presents a receiver based Givens transform in accordance with an embodiment of the invention (Embodiment 2.2.3.0 – Architecture)

Figure 30 presents a receiver based Givens transform in accordance with an embodiment of the invention (Embodiment 2.2.3.1 – Search Criteria)

Figure 31 presents a receiver based Givens transform in accordance with an embodiment of the invention (Embodiment 2.2.3.2 – Feedback method)

Figure 32 presents an SVD based pre-coding algorithm in accordance with an embodiment of the invention (SVD Decomposition >>> cost n^3)

Figure 33 presents an SVD based pre-coding algorithm in accordance with an embodiment of the invention (SVD Decomposition >>> cost n^3)

Figure 34 presents a MAC Support for CL-MIMO algorithm in accordance with an embodiment of the invention (Embodiment 3.0 -- FDD MIMO channel feedback (1))

Figure 35 presents a MAC Support for CL-MIMO algorithm in accordance with an embodiment of the invention (Embodiment 3.0 -- FDD MIMO channel feedback (2))

Figure 36 presents a MAC Support for CL-MIMO algorithm in accordance with an embodiment of the invention (Embodiment 3.1 -- TDD MIMO channel feedback)

Figure 37 presents a MAC Support for CL-MIMO algorithm in accordance with an embodiment of the invention (Embodiment 3.0 -- FDD MIMO channel feedback (1))

According to the embodiment of the invention shown in Figure 37, MIMO feedback channel allocation information element (MIMO_CQICH_Alloc_IE) is provided

This IE is used by BS to assign one or more fast feedback channel (CQICH) to a MSS for the MSS to provide MIMO feedback.

Table 1 -- MIMO_CQICH Alloc IE

Syntax	Size	Notes
MIMO_CQICH_Alloc_IE () {		
Extended UIUC	4 bits	0x??
Length	4 bits	Length in bytes of following fields
Num_Assignments	5 bits	Number of assignments in this IE
For (i = 0; i <Num_Assignments; i++)	-	-
{		
CID	16 bits	MSS basic CID
Duration(d)	3 bits	The CQICH is assigned to a MSS for $10x2^d$ frames; If d =0b000, the CQICH is deallocated; If d = 0b111, the MSS shall repor feedback information using the assigned resource until the BS commands for the MSS to stop
Frame offset	3 bits	The MSS starts to provide MIMO feedback at the frame which the number has the same 3LSB as the specified frame offset. If the current frame is specified, the MSS shall start transmit feedback in 8 frames
If (d !=ob000)		
{		
Num_CQICH_Allocation	4 bits	Number of CQICHs allocated to the MSS identified by the MSS basic CID

Num MIMO feedback	3 its	Numer of feedbacks formatted based on the Format index defined below
Length of band index	3 bits	Indication of the length of AMC band index
Length of CQI value index	2 bits	Indication of the length of CQI value index 0b00: 4 bits 0b01: 5 bits 0b10: 6bits 0b11: reserved
Format Index	3 bits	See Table Z
}		
}		
}		

After a MSS receives such a IE, the MSS may continuously transmit the following information defined in Table 1 during the assignment duration or until the CQICH(s) is deallocated. The information bits may be mapped to the assigned CQICH(s) in the following way:

For the first frame where CQICH(s) is allocated, the payload of first CQICH is first filled and the payload of second CQICH is filled up and so on until the all assigned CQICH(s) in the frame is filled up; for the following frames, the above is repeated

Table 2. MIMO feedback.

Syntax	Size	Notes
for (i=0; i < Num MIMO feedback; i++)		If the Num MIMO feedback > 1, the feedback, either layer based or AMC band based, shall be in the order so that the layer or AMC band who has the maximum CQI appears first.
{		
Feedback content formatted as indicated by format index	3 bits	See Table xx. Feedback format.
}		
If (Format index == 4)		
Average interference	4 bits	Average interference
If (Format index == 4)		
STTD/BLAST Selection	1 bit	0b0: STTD is selected 0b1:BLAST is selected
}		

Table 3 MIMO feedback formats

Format index	Feedback contents
1 (STTD/BLAST diversity permutation)	STTD/BLAST selection (1 bit) + Average CQI (the number of bits = length of CQI value index indicated in the corresponding MIMO_CHICH_Alloc_IE, e.g., 4/5/6 bits)
2 (STTD/BLAST antenna grouping for both diversity and AMC band permutations)	STTD/BLAST selection (1 bit) + Antenna group index (2 bits) + average CQI (the number of bits = length of CQI value index indicated in the corresponding MIMO_CHICH_Alloc_IE, e.g., 4/5/6 bits)
3 (STTD/BLAST for AMC band permutation)	Layer index (2 bits) + AMC band index (number of bits = Length of band_index indicated in the corresponding MIMO_CHICH_Alloc_IE) + CQI (the number of bits = length of CQI value index indicated in the corresponding MIMO_CHICH_Alloc_IE, e.g., 4/5/6 bits)
4 (feedback Channel H for AMC band permutation)	layer index(2 bits)+H (xx bits-depending on antenna configuration)
5 (feedback transmission weights for AMC band permutation)	layer index(2 bits)+W (xx bits-depending on antenna configuration) + CQI (the number of bits = length of CQI value index indicated in the corresponding MIMO_CHICH_Alloc_IE, e.g., 4/5/6 bits)
6 (feedback V matrix for AMC band permutation)	layer index(2 bits)+V (xx bits-depending on antenna configuration) + CQI (the number of bits = length of CQI value index indicated in the corresponding MIMO_CHICH_Alloc_IE, e.g., 4/5/6 bits)

Also provided in accordance with an embodiment of the invention is a MIMO_Feedback Request message

This message may be used by BS to request MIMO feedback information from a MSS who support MIMO operation.

Table 4 – MIMO Feedback request message format

Syntax	Size	Notes
MIMO Feedback Request message format () {	-	-
Num_MIMO_feedback	3 its	Numer of feedbacks formatted based on the Format index defined below
Length of band_index	3 bits	Indication of the length of AMC band index

Length of CQI value index	3 bits	Indication of the length of CQI value index
Format_Index	3 bits	See Table Z
}		

Also provided in accordance with an embodiment of the invention is a MIMO_Feedback Response message

This message may used by MSS to request MIMO feedback information to BS as a reply after receiving MIMO feedback request or as an unsolicited MIMO feedback.

Table 5 – MIMO Feedback response message format

Syntax	Size	Notes
MIMO Feedback Request message format () {		
Num_MIMO_feedback	3 its	Numer of feedbacks formatted based on the Format index defined below
Format_index	3 bits	
for (i=0; i < Num_MIMO_feedback; i++)		If the Num_MIMO_feedback > 1, the feedback, either layer based or AMC band based, shall be in the order so that the layer or AMC band who has the maximum CQI appears first.
{		
Feedback content formatted as indicated by format index	3 bits	See Table xx. Feedback format.
}		
If (Format_index == 4)		
Average_interference	4 bits	Average interference
If (Format_index == 3)		
STTD/BLAST_Selection	1 bit	0b0: STTD selected 0b1: BLAST selected
}		

Also provided in accordance with an embodiment of the invention is a MIMO feedback MAC header

This UP generic MAC header may be used by MSS to provide MIMO feedback information.
One or more MIMO feedback header(s) may be sent by a MSS at once if one header is not enough.

HT=1(1)	EC=1(1)	Type(6)=000001	MIMO feedback (8)
MIMO feedback (8)			MIMO feedback (8)
MIMO feedback (8)			HCS (8)

The Type (6) may be set to 000001 to indicate a MIMO feedback MAC header. In each MIMO feedback header, there are 32 bits payload may be used for the MIMO feedback purpose.

The mapping of feedback information bits (table Y) on to MIMO feedback header(s) may be provided as follows: the payload field in the first MIMO feedback header is filled and then the second, until preferably all the information bits are mapped.

Figure 38 presents a CQICH Based MIMO Channel Sounding Algorithm (1 transmit antenna) in accordance with an embodiment of the invention (Embodiment: 4.1.1 -- TDD MIMO channel sounding)

Figure 39 presents a CQICH Based MIMO Channel Sounding Algorithm (1 transmit antenna) in accordance with an embodiment of the invention (Embodiment: 4.1.2 -- Sounding CQICH channel for PUSC)

Figure 40 presents a CQICH Based MIMO Channel Sounding Algorithm (2 transmit antennas) in accordance with an embodiment of the invention (Embodiment: 4.1.3 -- Sounding CQICH channel for PUSC)

Figure 41 presents a CQICH Based MIMO Channel Sounding Algorithm (2 transmit antennas) in accordance with an embodiment of the invention (Embodiment: 4.1.4 -- Sounding CQICH channel for PUSC)

Figure 42 presents a CQICH Based MIMO Channel Sounding Algorithm (1 transmit antenna) in accordance with an embodiment of the invention (Embodiment: 4.1.5 -- Sounding CQICH channel for Optional PUSC)

Figure 43 presents a CQICH Based MIMO Channel Sounding Algorithm (2 transmit antennas) in accordance with an embodiment of the invention (Embodiment: 4.1.6 -- Sounding CQICH channel for Optional PUSC)

Figure 44 presents a CQICH Based MIMO Channel Sounding Algorithm (2 transmit antennas) in accordance with an embodiment of the invention (Embodiment: 4.1.7 -- Sounding CQICH channel for Optional PUSC)

Figure 45 presents a CQICH Based MIMO Channel Sounding Algorithm (2 transmit antennas) in accordance with an embodiment of the invention (Embodiment: 4.1.8 -- Sounding CQICH channel for Optional PUSC)

Figure 46 presents a CQICH Based MIMO Channel Sounding Algorithm in accordance with an embodiment of the invention (Embodiment: 4.1.9. -- sounding MIMO Feedback channel)

Figure 47 presents a CQICH Support of Differential Encoding Algorithm in accordance with an embodiment of the invention (Embodiment: 4.1.10. – mini tile support for differential CQI)

Figure 48 presents a space time coding for CQICH algorithm in accordance with an embodiment of the invention (SISO construct)

Figure 49 presents a space time coding for CQICH algorithm in accordance with an embodiment of the invention (Embodiment 4.2.1.-- STTD support)

Figure 50 presents a space time coding for CQICH algorithm in accordance with an embodiment of the invention (Embodiment 4.2.2. -- SM support)

Figure 51 presents a MIMO feedback channel ageing algorithm in accordance with an embodiment of the invention (Embodiment 4.3.1. – Receive ageing beam-former correction)

Figure 52 presents a MIMO feedback channel ageing algorithm in accordance with an embodiment of the invention (Embodiment 4.3.2. – Mitigation of ageing)

Figure 53 presents a pre-coding of MIMO pilot algorithm in accordance with an embodiment of the invention (Embodiment 4.4.1 – Pre-coding of MIMO pilot)

Figure 54 presents a pre-coding of MIMO pilot algorithm in accordance with an embodiment of the invention (Embodiment 4.4.2 – Pre-coding of MIMO pilot)

Figure 55 presents a pre-coding of MIMO pilot algorithm in accordance with an embodiment of the invention (Embodiment 4.4.3 – MIMO pilot of pre-coding large antenna array)

The IEEE 802.16(a, d and e) and 802.11(n) standards are hereby incorporated by reference.

Figure 56 provides an overview of Vector Pre-coding (code-book construction) for purposes of context and comparison

Figure 57 provides an overview of Vector Pre-coding (code-book optimization) for purposes of context and comparison

Figure 58 provides an overview of Vector Pre-coding (vector quantize channel) for purposes of context and comparison

Figure 59 provides an overview of Matrix Pre-coding (column by column vector quantize channel-1) for purposes of context and comparison

Figure 60 provides an overview of Matrix Pre-coding (column by column vector quantize channel-2) for purposes of context and comparison

Figure 61 provides an overview of Matrix Pre-coding (decompression of quantized channel-1) for purposes of context and comparison

Figure 62 provides an overview of Matrix Pre-coding (decompression of quantized channel-2) for purposes of context and comparison

Figure 63 provides an overview of Matrix Pre-coding (code book design) for purposes of context and comparison

Figure 64 provides an overview of Matrix Pre-coding (code book design) for purposes of context and comparison

Figure 65 provides an overview of Matrix Pre-coding (vector quantize channel) for purposes of context and comparison

WE CLAIM:

A method comprising:
at a basestation:
broadcasting pilot information to one or more receivers; and
receiving channel information from at least one of said one or more receivers in response to said pilot information,
wherein said channel information is compressed using differential encoding

A method comprising:
at a receiver, receiving pilot information broadcast from a basestation; and
in response to said pilot information, transmitting channel information to said basestation,
wherein said channel information is compressed using differential encoding

A method comprising:
at a basestation:
broadcasting pilot information to one or more receivers; and
receiving channel information from at least one of said one or more receivers in response to said pilot information,
wherein said channel information is compressed using a givens rotation transformation.

A method comprising:
at a receiver, receiving pilot information broadcast from a basestation; and
in response to said pilot information, transmitting channel information to said basestation,
wherein said channel information is compressed using a givens rotation transformation

A method comprising:
at a basestation having a plurality of antennas:
broadcasting pilot information to one or more receivers;
receiving channel information from at least one of said one or more receivers in response to said pilot information, and
assigning one or more antennas to said at least one of said or more users based on said received compressed channel information.

A system comprising:
either transmit or receive circuitry as is appropriate; and
circuitry adapted to carry out the methods set out above.

Figure 1

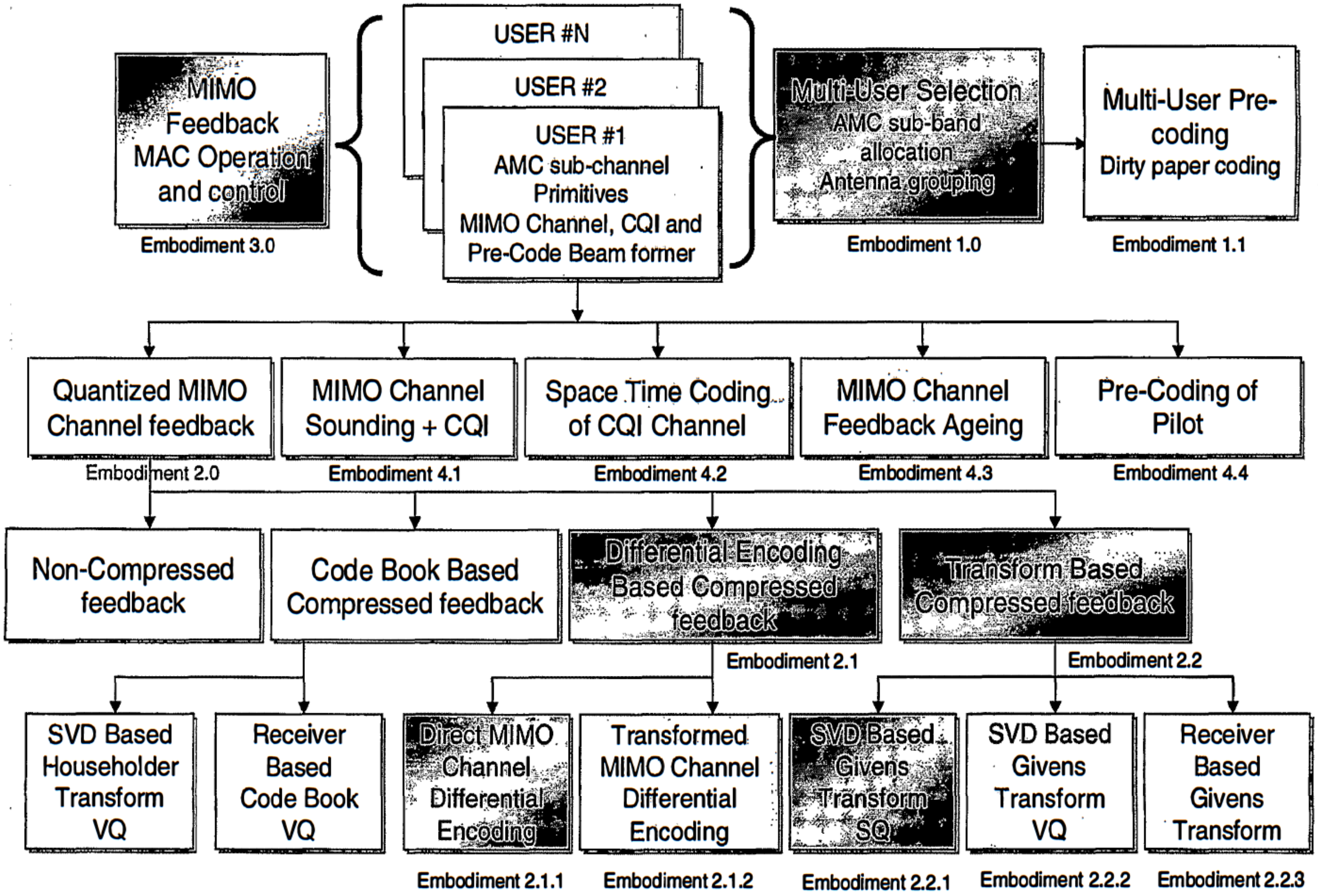
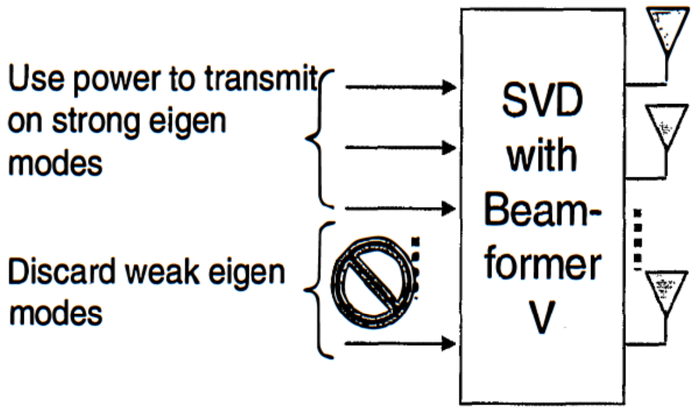
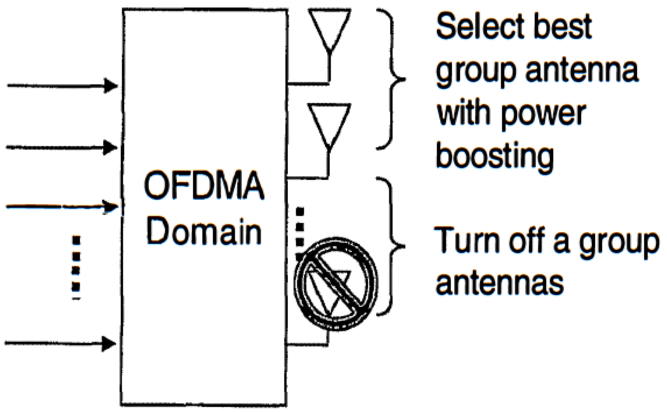

MIMO Feedback MAC Operation and control
Embodiment 3.0
USER #N
USER #2
USER #1
AMC sub-channel Primitives
MIMO Channel, CQI and Pre-Code Beam former
Multi-User Selection
AMC sub-band allocation
Antenna grouping
Embodiment 1.0
Multi-User Pre-coding
Dirty paper coding
Embodiment 1.1
Quantized MIMO Channel feedback
Embodiment 2.0
MIMO Channel Sounding + CQI
Embodiment 4.1
Space Time Coding of CQI Channel
Embodiment 4.2
MIMO Channel Feedback Ageing
Embodiment 4.3
Pre-Coding of Pilot
Embodiment 4.4
Non-Compressed feedback
Code Book Based Compressed feedback
Differential Encoding Based Compressed feedback
Embodiment 2.1
Transform Based Compressed feedback
Embodiment 2.2
SVD Based Householder Transform VQ
Receiver Based Code Book VQ
Direct MIMO Channel Differential Encoding
Embodiment 2.1.1
Transformed MIMO Channel Differential Encoding
Embodiment 2.1.2
SVD Based Givens Transform SQ
Embodiment 2.2.1
SVD Based Givens Transform VQ
Embodiment 2.2.2
Receiver Based Givens Transform
Embodiment 2.2.3

Figure 2



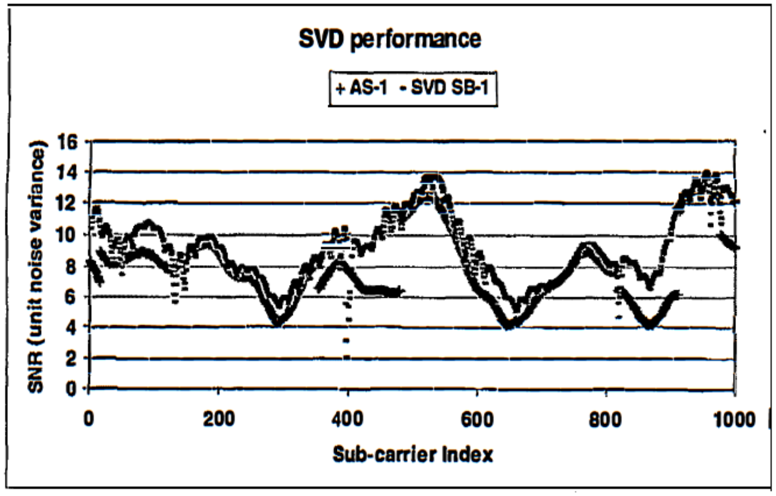
- SVD is optimal in terms of the best channel matching transmission and achieving the link level Shannon capacity
- However, SVD typically requires a large amount of computing and a large amount of CSI feedback in the FFD case.



- Antenna grouping is based on the selection of sub-set antenna from available antennas by the terminal based on simple criterion
- The terminal generally needs to feedback very little information to the Base station
- Antenna grouping criterion may be based on eigenvalue rather than on determinant.
- This may avoid selection being dominated by weak layers.
- Typically degradation due to antenna selection is smaller when the group size is larger

Figure 3

- Antenna grouping achieves very close to SVD performance with significantly low complexity
- SVD generally provides optimal performance when AMC can be performed on each individual layer.
- When AMC is not layer based, the performance difference is generally smaller due to imbalanced layer SNR distribution.
- Preferably, therefore, AMC is implemented on per layer basis.
- When SVD is used, the 4-th layer can generally be eliminated, meaning only 3 columns of V-matrix generally need to be fed back to the transmitter.



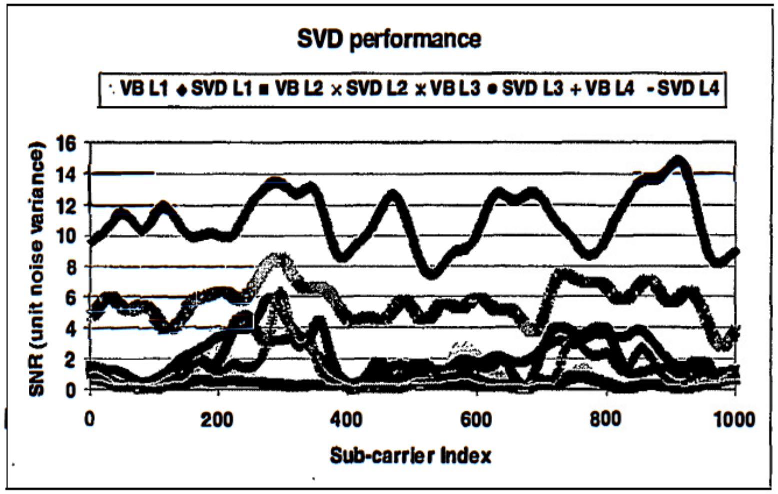


Figure 4

- With channel estimation form the pilots :MIMO pre/mid amble or MIMO scattered pilots may compute criterion including the following:
- Select the transmission modes
  - STTD
  - SM

$$\overset{\overset{\text{STTD}}{\downarrow}}{\sum_{i=1}^{N}\sum_{j=1}^{M}\left|h_{ij}\right|^{2}} > \frac{\overset{\overset{\text{SM}}{\downarrow}}{\gamma_0^{M-1}}}{\prod_{i=1}^{M}\left\|g_i\right\|^{2}}$$

Where $\gamma_0 = \frac{P}{M\sigma^2}$ and g_i is the row of matrix G

$$G = (H'H)^{-1}H'$$

Figure 5

- For the STTD mode, the antenna group selection is based on criterion including the following:

$$SS_{STTD} = \arg\max_{SS} \sum_{i=1}^{N} \sum_{j=1}^{M_{SS}} \left| h_{ij} \right|^2$$

- For the SM mode, the antenna group selection is based on criterion including the following:

$$SS_{V-BLAST} = \arg\min_{SS} \prod_{i=1}^{M_{SS}} \left\| g_i \right\|^2$$

Figure 1

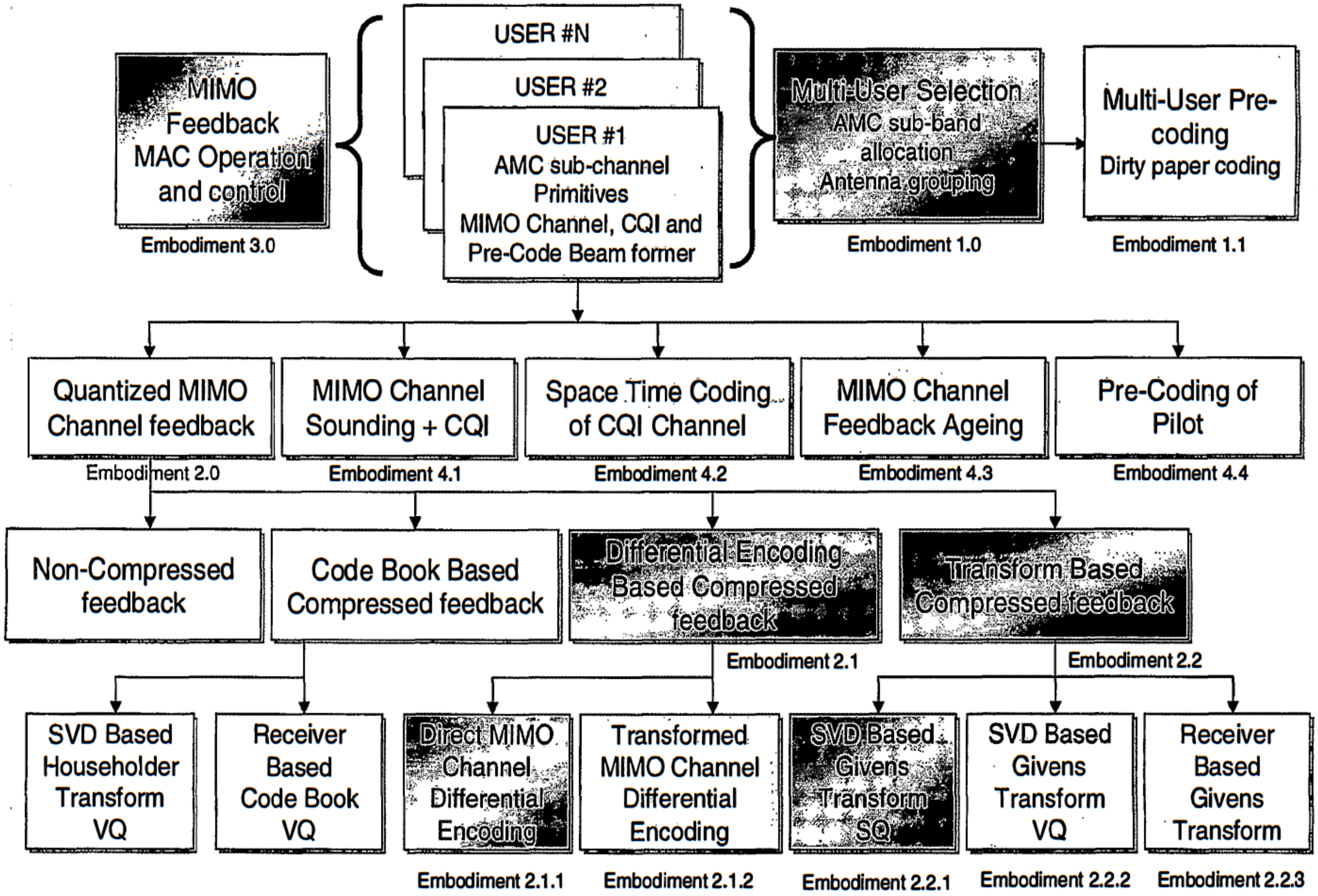
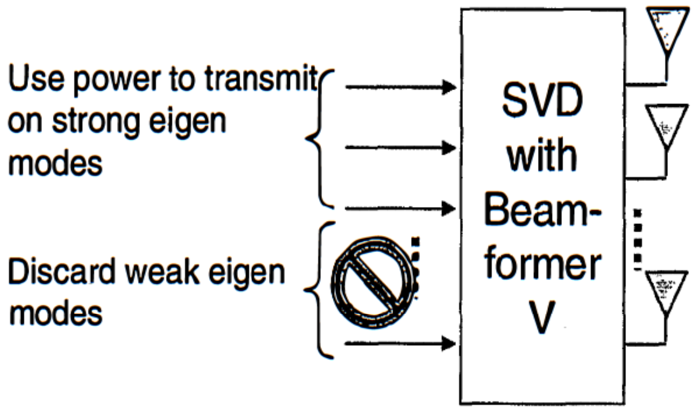
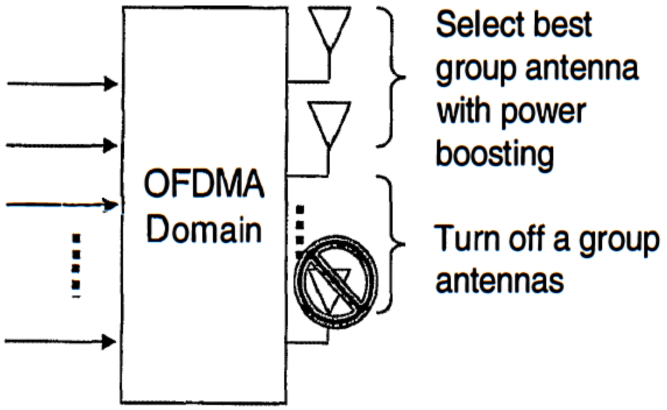

MIMO Feedback MAC Operation and control
Embodiment 3.0
USER #N
USER #2
USER #1
AMC sub-channel Primitives
MIMO Channel, CQI and Pre-Code Beam former
Multi-User Selection
AMC sub-band allocation
Antenna grouping
Embodiment 1.0
Multi-User Pre-coding
Dirty paper coding
Embodiment 1.1
Quantized MIMO Channel feedback
Embodiment 2.0
MIMO Channel Sounding + CQI
Embodiment 4.1
Space Time Coding of CQI Channel
Embodiment 4.2
MIMO Channel Feedback Ageing
Embodiment 4.3
Pre-Coding of Pilot
Embodiment 4.4
Non-Compressed feedback
Code Book Based Compressed feedback
Differential Encoding Based Compressed feedback
Embodiment 2.1
Transform Based Compressed feedback
Embodiment 2.2
SVD Based Householder Transform VQ
Receiver Based Code Book VQ
Direct MIMO Channel Differential Encoding
Embodiment 2.1.1
Transformed MIMO Channel Differential Encoding
Embodiment 2.1.2
SVD Based Givens Transform SQ
Embodiment 2.2.1
SVD Based Givens Transform VQ
Embodiment 2.2.2
Receiver Based Givens Transform
Embodiment 2.2.3

Figure 2



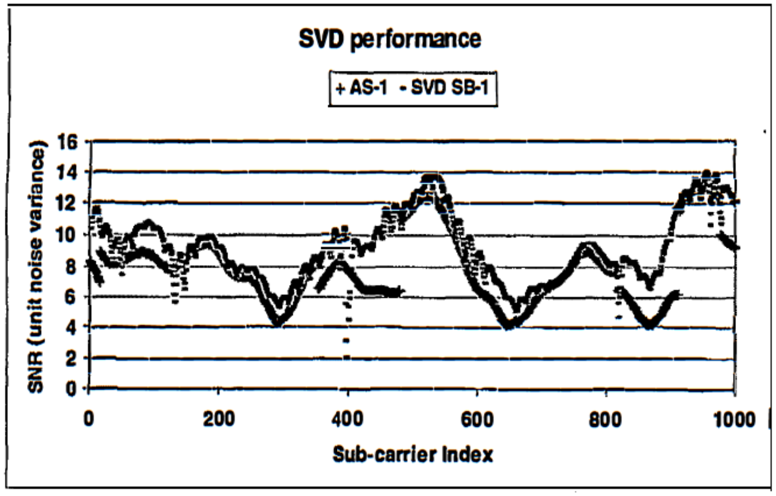
- SVD is optimal in terms of the best channel matching transmission and achieving the link level Shannon capacity
- However, SVD typically requires a large amount of computing and a large amount of CSI feedback in the FFD case.



- Antenna grouping is based on the selection of sub-set antenna from available antennas by the terminal based on simple criterion
- The terminal generally needs to feedback very little information to the Base station
- Antenna grouping criterion may be based on eigenvalue rather than on determinant.
- This may avoid selection being dominated by weak layers.
- Typically degradation due to antenna selection is smaller when the group size is larger

Figure 3

- Antenna grouping achieves very close to SVD performance with significantly low complexity
- SVD generally provides optimal performance when AMC can be performed on each individual layer.
- When AMC is not layer based, the performance difference is generally smaller due to imbalanced layer SNR distribution.
- Preferably, therefore, AMC is implemented on per layer basis.
- When SVD is used, the 4-th layer can generally be eliminated, meaning only 3 columns of V-matrix generally need to be fed back to the transmitter.



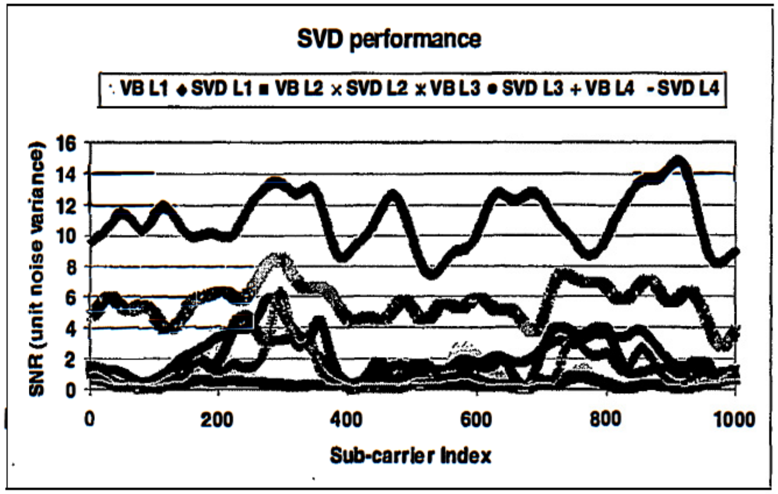


Figure 4

- With channel estimation form the pilots :MIMO pre/mid amble or MIMO scattered pilots may compute criterion including the following:
- Select the transmission modes
  - STTD
  - SM

$$\overset{\overset{\text{STTD}}{\downarrow}}{\sum_{i=1}^{N}\sum_{j=1}^{M}\left|h_{ij}\right|^{2}} > \overset{\overset{\text{SM}}{\downarrow}}{\frac{\gamma_{0}^{M-1}}{\prod_{i=1}^{M}\left\|g_{i}\right\|^{2}}}$$

Where $\gamma_0 = \frac{P}{M\sigma^2}$ and g_i is the row of matrix G

$$G = (H'H)^{-1}H'$$

Figure 5

- For the STTD mode, the antenna group selection is based on criterion including the following:

$$SS_{STTD} = \arg\max_{SS} \sum_{i=1}^{N} \sum_{j=1}^{M_{SS}} \left| h_{ij} \right|^2$$

- For the SM mode, the antenna group selection is based on criterion including the following:

$$SS_{V-BLAST} = \arg\min_{SS} \prod_{i=1}^{M_{SS}} \left\| g_i \right\|^2$$

Figure 6

For the STTD mode, in accordance with an embodiment of the invention,

$$\xi_j = \sum_{i=1}^{N} \left| h_{ij} \right|^2$$

wherein

$$L_k = \arg\max_{j \in \{M\}} \left(\xi_j \right)$$

And wherein transmission on an antenna is stopped when:

$$L_i < \alpha L_k$$

In accordance with an embodiment of the invention, for the SM mode, if $Q = \frac{\lambda_{\max}}{\lambda_{\min}} \geq \beta$ then a new subset of antennas then can be selected according to criterion including maximum determinant criterion:

$$S_a = \arg\max\left(\det\left(H'_a H_a\right)\right)$$

where Ha is the channel matrix of the new sub-MIMO size. α and β are predefined thresholds

Figure 6

For the STTD mode, in accordance with an embodiment of the invention,

$$\xi_j = \sum_{i=1}^{N} \left| h_{ij} \right|^2$$

wherein

$$L_k = \arg\max_{j \in \{M\}} \left(\xi_j \right)$$

And wherein transmission on an antenna is stopped when:

$$L_i < \alpha L_k$$

In accordance with an embodiment of the invention, for the SM mode, if $Q = \frac{\lambda_{\max}}{\lambda_{\min}} \geq \beta$ then a new subset of antennas then can be selected according to criterion including maximum determinant criterion:

$$S_a = \arg\max\left(\det\left(H'_a H_a\right)\right)$$

where Ha is the channel matrix of the new sub-MIMO size. α and β are predefined thresholds

Figure 6 (cont')

- Antenna grouping procedure for IEEE802.16 as an example
  - Decide antenna group size for STTD (matrix A) and SM mode (Matrix B and C),
  - Select transmit antenna sub-sets based on selected size.
  - Decide transmit mode: STTD vs. SM
  - If SM is selected and the antenna group size is larger than SM layers, then use Matrix B, otherwise, use matrix C

Figure 6A

The BTS possessing M transmit antennas to transmit to K users each with M receive antennas

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{s} + \mathbf{w}_k, \quad 1 \le k \le K \qquad (1)$$

where $\mathbf{H}_k \in \mathcal{C}^{N \times M}$ denotes the channel matrix from the base station to the k^{th} user, $\mathbf{s} \in \mathcal{C}^{M \times 1}$ represents the transmitted vector, and $\mathbf{y}_k \in \mathcal{C}^{N \times 1}$ signifies received vector by the k^{th} user. The vector $\mathbf{w}_k \in \mathcal{C}^{N \times 1}$ is white Gaussian noise with zero-mean and unit-variance.

In the proposed method, the transmitted vector $\mathbf{s}$ carries information for M users, defined as follows,

$$\mathbf{s} = \sum_{j=1}^{M} d_{\pi(j)} \mathbf{v}_{\pi(j)} \qquad (2)$$

where $\pi(j)$, $j = 1 \ldots M$ are the indexes of a subset of users so-called *active users*, $\mathbf{v}_{\pi(j)} \in \mathcal{C}^{M \times 1}$, $j = 1 \ldots M$ are a set of orthogonal vectors, and $d_{\pi(j)}$ includes information for the user $\pi(j)$. In addition, dirty-paper pre-coding is used on top of the system such that if $i > j$, the interference of the user $\pi(i)$ over user $\pi(j)$ is zero.

For demodulation, the user $\pi(j)$ multiplies the received vector to a normal vector $\mathbf{u}_{\pi(j)}^{\prime}$, where $(.)^{\prime}$ denotes transpose conjugate operation.

Figure 6B

1) Set $j = 1$ and the condition matrix $\mathbf{G}_{eq} = \mathbf{0}_{M \times M}$.

2) Find $\sigma^2_{\pi(j)}$ where

$$\sigma^2_{\pi(j)} = \max_r \max_x \mathbf{x}'\mathbf{H}_r'\mathbf{H}_r\mathbf{x}.$$

$$\mathbf{x}'\mathbf{x} = 1 \qquad (3)$$

$$\mathbf{G}_{eq}'\mathbf{x} = 0$$

Set $\pi(j)$ and $\mathbf{v}_{\pi(j)}$ be equal to the optimizing parameter r and $\mathbf{x}$, respectively.

3) Set

$$\mathbf{u}_{\pi(j)} = \frac{1}{\sigma_{\pi(j)}}\mathbf{H}_{\pi(j)}\mathbf{v}_{\pi(j)}. \qquad (4)$$

4) Set $\mathbf{g}_j = \mathbf{v}_{\pi(j)}$, where $\mathbf{g}_j$ is the j^{th} column of the matrix $\mathbf{G}_{eq}$.

5) $j \leftarrow j + 1$. If $j \leq M$ go to step two, otherwise stop.

Figure 6C

1) Set $j = 1$ and $\mathbf{G}_{eq} = \mathbf{0}_{M \times M}$.

2) Each user calculates $\sigma^2_{r(j)}$, defined as follows

$$\sigma^2_{r(j)} = \max_{x} \mathbf{x}'\mathbf{H}_r'\mathbf{H}_r\mathbf{x}.$$

$$\mathbf{x}'\mathbf{x} = 1 \qquad (5)$$

$$\mathbf{G}_{eq}'\mathbf{x} = 0$$

$\mathbf{v}_{r(j)}$ represents the optimizing parameter $\mathbf{x}$.

3) Each user calculates

$$\mathbf{u}_{r(j)} = \frac{1}{\sigma_{r(j)}}\mathbf{H}_r\mathbf{v}_{r(j)}. \qquad (6)$$

4) Each user sends $\sigma^2_{r(j)}$ and $\mathbf{v}_{r(j)}$ to the base station, if $\sigma^2_{r(j)} \geq th(j)$. $th(j)$ is a threshold which is predetermined by the base station.

5) Base station selects the user with the largest $\sigma^2_{r(j)}$. Let $\pi(j)$ be the index of the selected user. The corresponding gain and coordinate of that user are $\sigma^2_{\pi(j)}$ and $\mathbf{v}_{\pi(j)}$, respectively.

6) The $\pi(j)^{th}$ user sends $\mathbf{u}_{\pi(i)}'\mathbf{H}_{\pi(j)}\mathbf{v}_{\pi(i)}$, $i = 1, \ldots, j-1$, to the base station.

7) Base station sends $\mathbf{v}_{\pi(j)}$ to all users. All users include $\mathbf{v}_{\pi(j)}$ in $\mathbf{G}_{eq}$ as the j^{th} column.

8) $j \leftarrow j + 1$. If $j \leq M$ go to step two, otherwise stop.

Figure 7

Feedback MIMO channel and CQI separately in accordance with an embodiment of the invention

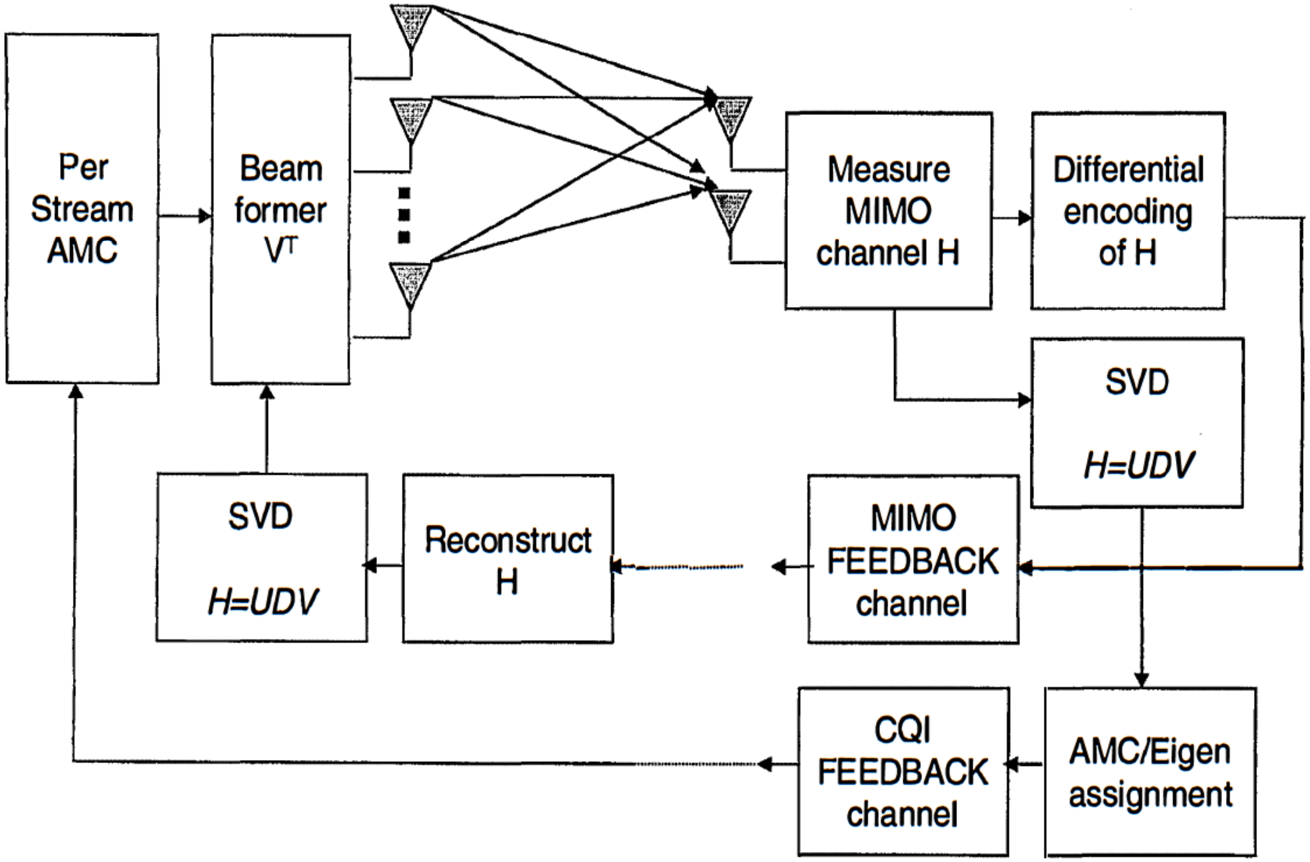


Figure 8

Feedback MIMO channel and CQI jointly in accordance with an embodiment of the invention

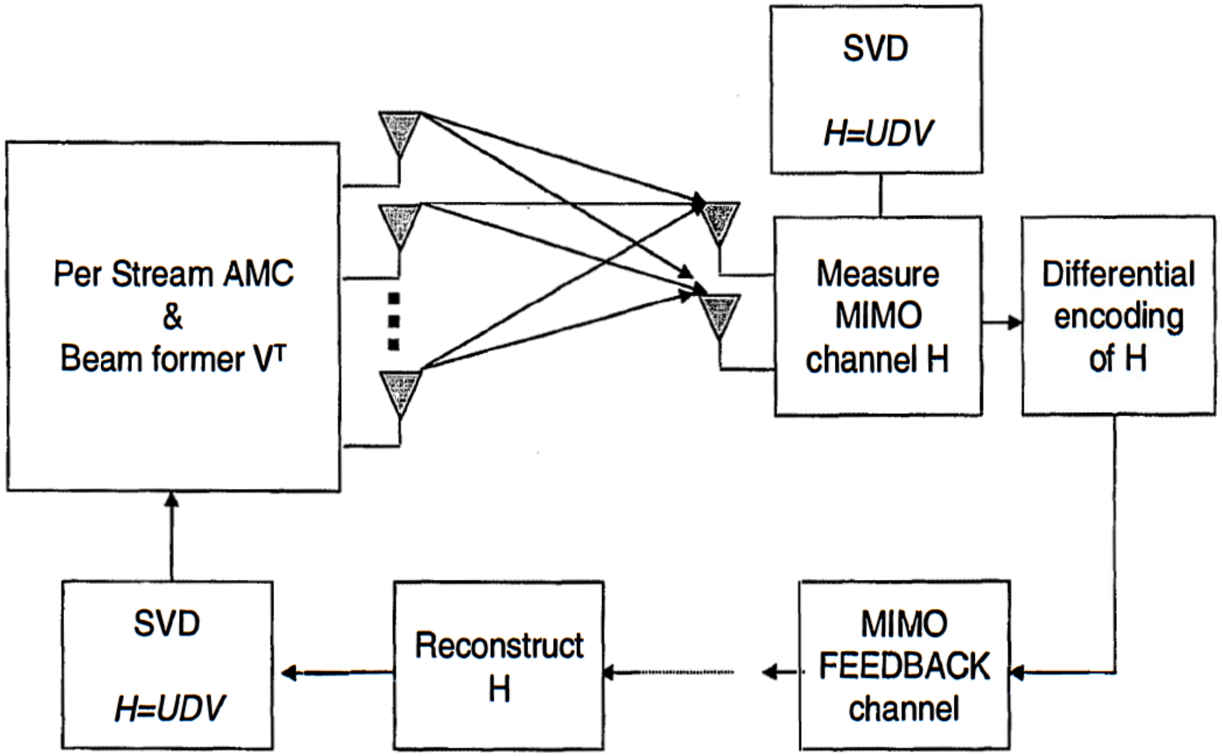


Figure 9

Differential scalar quantizer in accordance with an embodiment of the invention

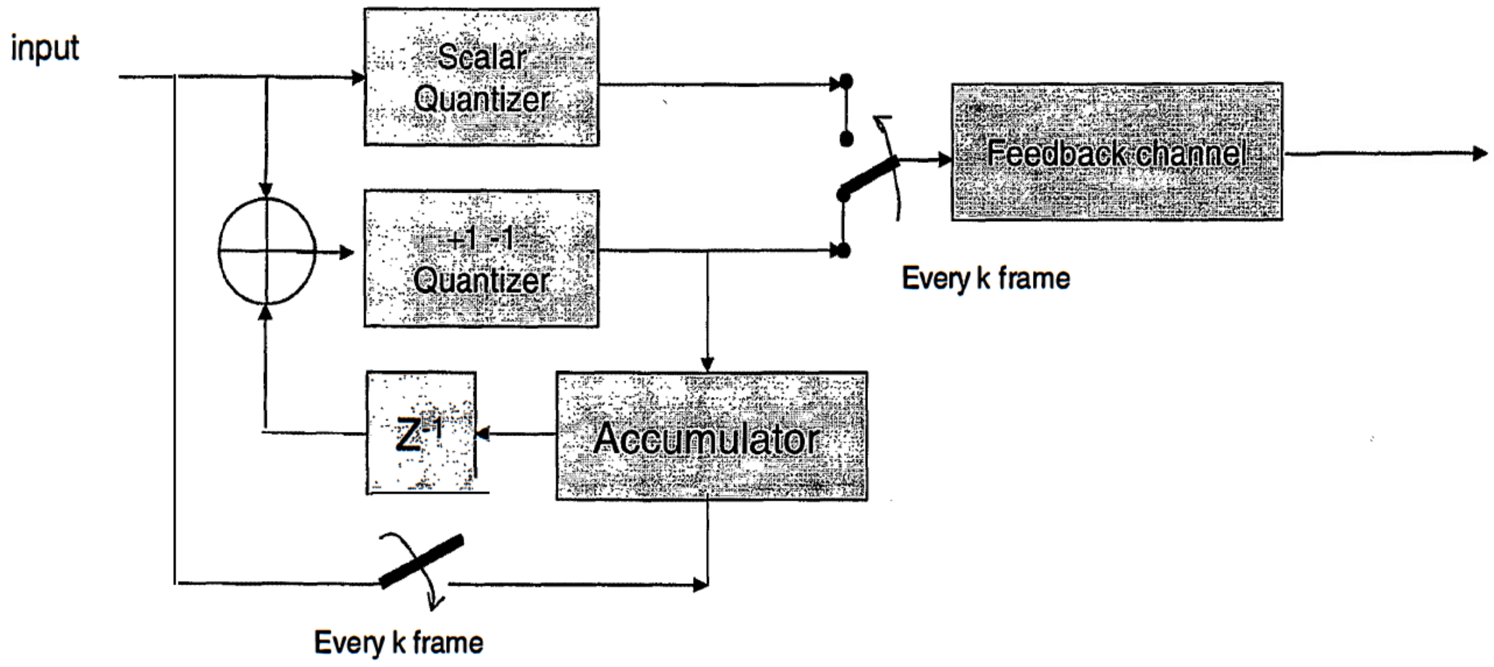


Figure 10

Differential scalar quantizer in accordance with an embodiment of the invention

$\Delta\Sigma$ modulation encoder: In accordance with a preferred embodiment of the invention a $\Delta\Sigma$ modulator that is simple to implement and yet meets the system requirement is desirable. The 1st-order $\Delta\Sigma$ modulation encoders are shown in Figure 11. An offset and limiter are applied to the C/I input. The C/I_Offset is used to move the C/I dynamic range within the range required by $\Delta\Sigma$. The limiter may be used to prevent $\Delta\Sigma$ overflow. The input level is often less than the quantizer step size Δ and hence is denoted by $\alpha\Delta$ where $\alpha < 1$ dependent on $\Delta\Sigma$ type. Note that a dither signal may also be applied to the 1st-order $\Delta\Sigma$ modulator input to eliminate the limit cycle inherent in the 1st-order modulators and in this instance is a sequence ($\Delta/8$, $-\Delta/8$,). These are classical $\Delta\Sigma$ modulators with the exception there are no delays in the signal paths.

Decoding filter: To maximize the SNR and minimize the delay, an nth-order IIR filter may be used to evaluate the performance. The IIR filter includes *n* identical one-pole filters with the transfer function defined as follows:

$$H(z) = \left(\frac{1-a}{1-az^{-1}} \right)^{n} \qquad \text{n is integer}$$

Figure 11

$\Delta\Sigma$ modulator 1-bit quantizer in accordance with an emdodiment of the invention

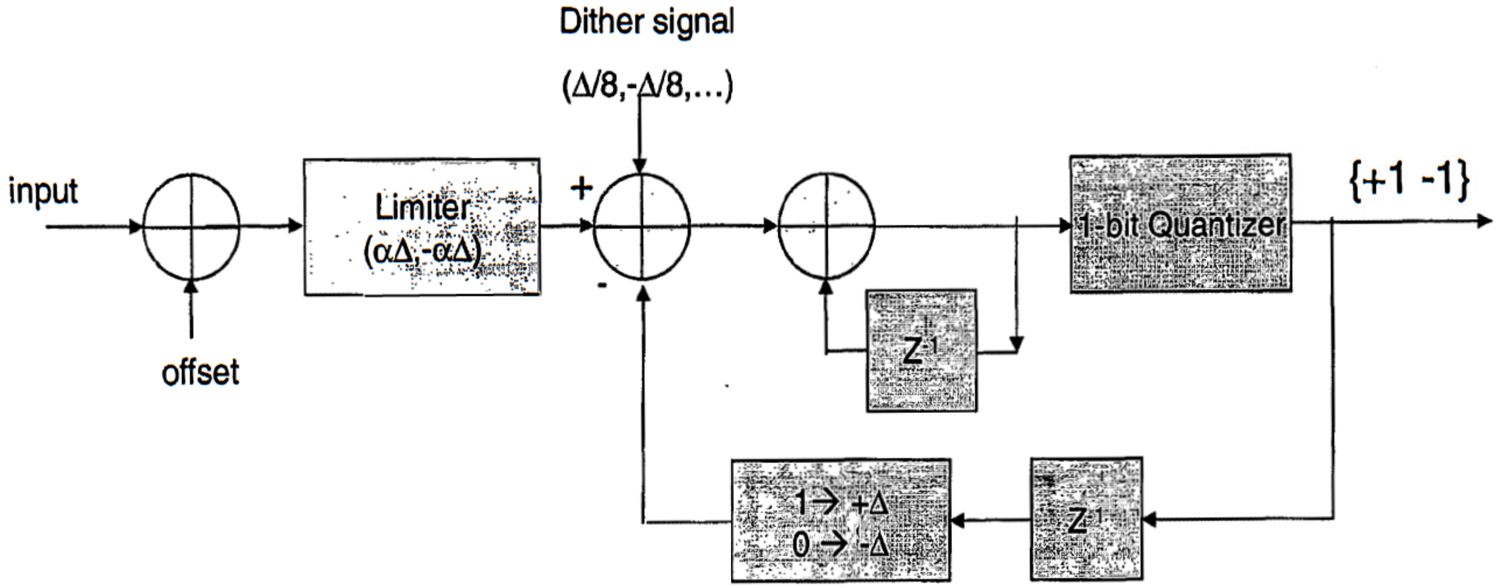
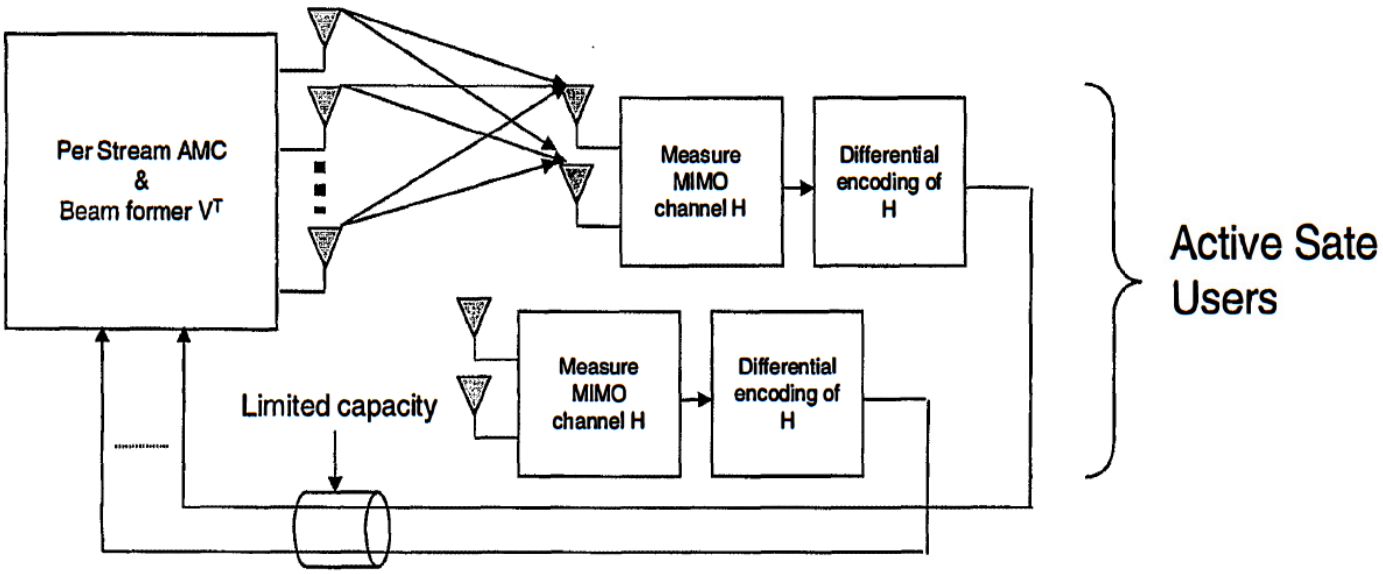


Figure 12



- Differential feedback, and every k frames with full feedback MIMO channel feedback every k frames
- See MAC message.

Figure 13

Number of CQI bits streams

	1	2	4
2	4	8	16
3	6	12	24
4	8	16	32
8	16	32	64

Number of CQI channels (4bit)

	1	2	4
2	1	2	4
3	2	3	6
4	2	4	8
8	4	8	16

Number of CQI channels (6bit)

	1	2	4
2	1	2	3
3	1	2	4
4	2	3	6
8	3	6	11

- The differential encoder output may be grouped together to map to the existing CQI feedback channel or MIMO feedback channel

Figure 14

- The SVD based unitary matrix includes n^2-n independent complex parameters
- Therefore, in accordance with an embodiment, $2(n^2-n)$ bits are used for the differential quantization of unitary matrix
- In accordance with this embodiment an n stream CQI channel is used, preferably 4 bits each
- According to this embodiment, therefore, the total requirement for the unitary matrix feedback is $2n^2+2n$
- However for the direct differential encoding approach the total feedback used is $2n^2$ including the CQI information, since it is embedded in H

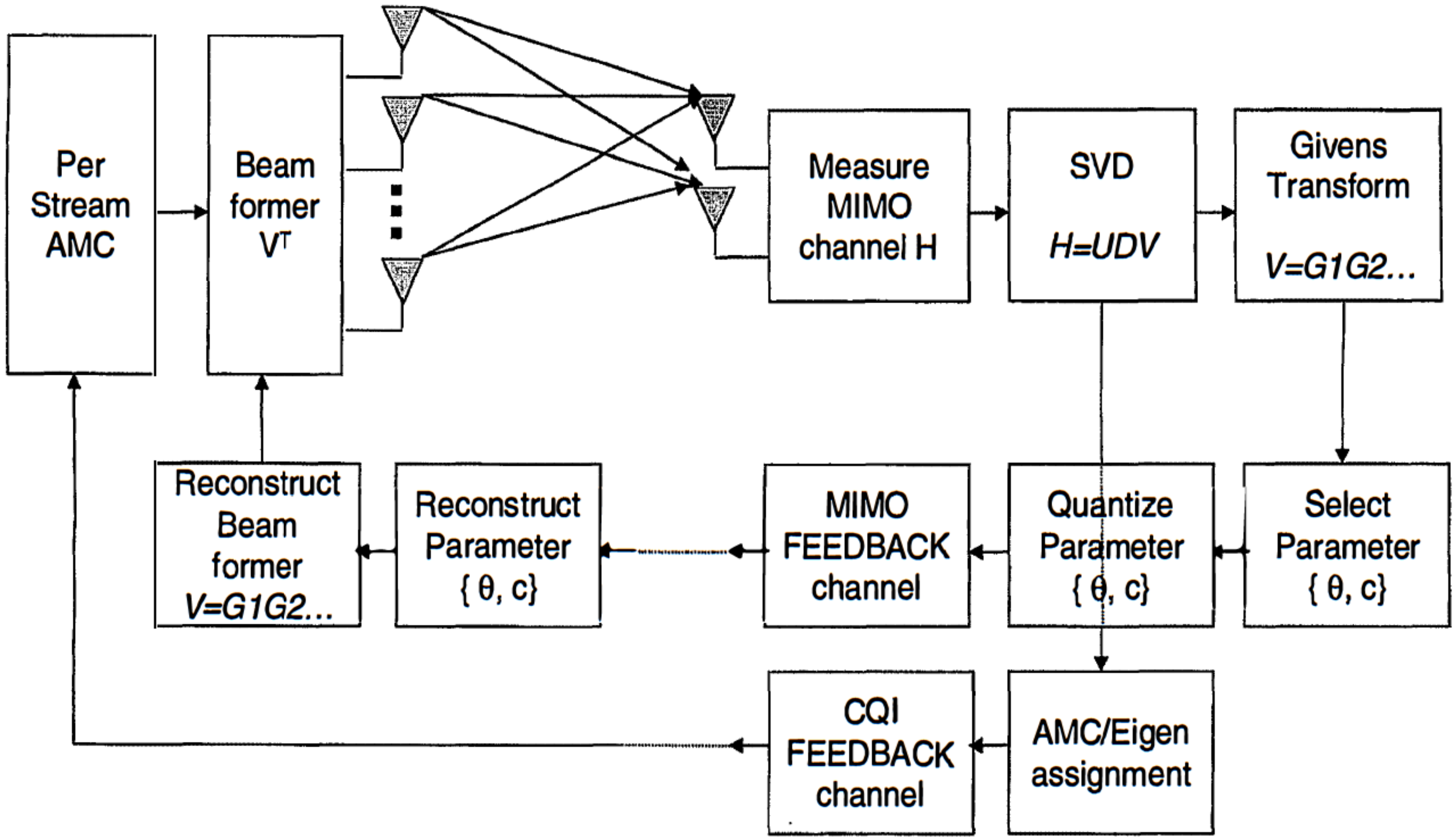
Feedback Requriement (NxN MIMO)			
# of Tx	**Unitary Matrix**	**Direct H Matrix**	**Complexity**
2	12	8	150.00%
3	24	18	133.33%
4	40	32	125.00%
5	60	50	120.00%
6	84	72	116.67%
7	112	98	114.29%
8	144	128	112.50%

Figure 15

In accordance with an embodiment of the invention:

- The terminal computes the complex value antenna weights
- The differential encoding is applied to feedback the complex weights
- The feedback requirement is minimized (2n bits)

Figure 16



For V matrix feedback, the BS is able to verify the integrity of the received matrix V by exploiting the orthogonality of the matrix

Figure 17

Givens rotation for 2 transmit antenna (Format-A) includes:

$$G = \begin{bmatrix} \hat{c} & |\hat{s}|e^{j\hat{\theta}} \\ -|\hat{s}|e^{-j\hat{\theta}} & \hat{c} \end{bmatrix}$$

The parameter space includes $\theta=\{-\pi +\pi\}$ and $c =\{ 0, 1\}$ $s=(1-c^2)^{1/2}$

Givens rotation for 2 transmit antenna (Format-B) includes:

$$G = \begin{bmatrix} \cos(\eta) & e^{j\theta}\sin(\eta) \\ -e^{-j\theta}\sin(\eta) & \cos(\eta) \end{bmatrix}$$

The parameter space includes $\theta=\{-\pi +\pi\}$ and $\eta=\{-\pi +\pi\}$

Figure 18

Givens rotation for 3 transmit antenna (Format-A) includes:

$$G(k,i) = \overset{G_1}{\begin{bmatrix} c & s & 0 \\ -s^* & c & 0 \\ 0 & 0 & 1 \end{bmatrix}} \overset{G_2}{\begin{bmatrix} c & 0 & s \\ 0 & 1 & 0 \\ -s^* & 0 & c \end{bmatrix}} \overset{G_3}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c & s \\ 0 & -s^* & c \end{bmatrix}}$$

The parameter space includes

$\theta_1=\{-\pi\ +\pi\}$ and $c_1=\{0,1\}$ for G_1

$\theta_2=\{-\pi\ +\pi\}$ and $c_2=\{0, 1\}$ for G_2

$\theta_3=\{-\pi\ +\pi\}$ and $c_3=\{0, 1\}$ for G_3

The scalar quantizers (Lloyd-Max) includes:

$\theta_1 \rightarrow$ 2bit and $c_1 \rightarrow$ 1bit

$\theta_2 \rightarrow$ 2bit and $c_2 \rightarrow$ 1bit

$\theta_3 \rightarrow$ 2bit and $c_3 \rightarrow$ 1bit

Figure 19

Givens rotation for 4 transmit antenna (Format-A) includes:

$$G(k,i)=\overset{G_1}{\begin{bmatrix} c & s & 0 & 0 \\ -s^* & c & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}\overset{G_2}{\begin{bmatrix} c & 0 & s & 0 \\ 0 & 1 & 0 & 0 \\ -s^* & 0 & c & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}\overset{G_3}{\begin{bmatrix} c & 0 & 0 & s \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s^* & 0 & 0 & c \end{bmatrix}}\overset{G_4}{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c & s & 0 \\ 0 & -s^* & c & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}\overset{G_5}{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c & 0 & s \\ 0 & 0 & 1 & 0 \\ 0 & -s^* & 0 & c \end{bmatrix}}\overset{G_6}{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c & s \\ 0 & 0 & -s^* & c \end{bmatrix}}$$

The parameter space includes

$\theta_1=\{-\pi\ +\pi\}$ and $c_1=\{0,1\}$ for G_1

$\theta_2=\{-\pi\ +\pi\}$ and $c_2=\{0,1\}$ for G_2

$\theta_3=\{-\pi\ +\pi\}$ and $c_3=\{0,1\}$ for G_3

$\theta_4=\{-\pi +\pi\}$ and $c_4=\{0,1\}$ for G_1

$\theta_5=\{-\pi\ +\pi\}$ and $c_5=\{0, 1\}$ for G_2

$\theta_6=\{-\pi\ +\pi\}$ and $c_6=\{0, 1\}$ for G_3

The scalar quantizers (Lloyd-Max) includes:

θ_1 → 2bit and c_1 → 1bit

θ_2 → 2bit and c_2 → 1bit

θ_3 → 2bit and c_3 → 1bit

θ_4 → 2bit and c_4 → 1bit

θ_5 → 2bit and c_5 → 1bit

θ_6 → 2bit and c_6 → 1bit

Figure 20

Givens rotation for n transmit antenna (Format-A) includes:

$$V = \prod_{k=1}^{n-1} \prod_{i=1}^{n-k} G(k,i)$$

$$G(k,i) = \begin{bmatrix} 1 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & c & \cdots & s & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & -s^* & \cdots & c & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & 1 \end{bmatrix}$$

Figure 21

In accordance with an embodiment of the invention, weak eigen modes may be discarded with application of water filling in the eigen domain

Eigen vector #1

$$V=\begin{bmatrix} c & s & 0 \\ -s^* & c & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} c & 0 & s \\ 0 & 1 & 0 \\ -s^* & 0 & c \end{bmatrix}$$

Eigen vector #1,2&3

$$V=\begin{bmatrix} c & s & 0 \\ -s^* & c & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} c & 0 & s \\ 0 & 1 & 0 \\ -s^* & 0 & c \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & c & s \\ 0 & -s^* & c \end{bmatrix}$$

Figure 22

Eigen vector #1

$$V=\begin{bmatrix} c & s & 0 & 0\\ -s^* & c & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} c & 0 & s & 0\\ 0 & 1 & 0 & 0\\ -s^* & 0 & c & 0\\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} c & 0 & 0 & s\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ -s^* & 0 & 0 & c \end{bmatrix}$$

Eigen vector #1&2

$$V=\begin{bmatrix} c & s & 0 & 0\\ -s^* & c & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} c & 0 & s & 0\\ 0 & 1 & 0 & 0\\ -s^* & 0 & c & 0\\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} c & 0 & 0 & s\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ -s^* & 0 & 0 & c \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & 0\\ 0 & c & s & 0\\ 0 & -s^* & c & 0\\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & 0\\ 0 & c & 0 & s\\ 0 & 0 & 1 & 0\\ 0 & -s^* & 0 & c \end{bmatrix}$$

Eigen vector #1,2,3 & 4

$$V=\begin{bmatrix} c & s & 0 & 0\\ -s^* & c & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} c & 0 & s & 0\\ 0 & 1 & 0 & 0\\ -s^* & 0 & c & 0\\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} c & 0 & 0 & s\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ -s^* & 0 & 0 & c \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & 0\\ 0 & c & s & 0\\ 0 & -s^* & c & 0\\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & 0\\ 0 & c & 0 & s\\ 0 & 0 & 1 & 0\\ 0 & -s^* & 0 & c \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & c & s\\ 0 & 0 & -s^* & c \end{bmatrix}$$

Figure 23

- According to an embodiment of the invention, the bit allocation may be designed for full scalar quantizer and partial scalar quantizer
- Based on the pre-coding QoS requirement, the bit allocation may provide a tradeoff between performance and feedback penalty
- For Givens parameter in Format-A
  - Theta is uniformly distributed → more bits
  - C is non-uniform distributed → less bits
  - Some in-significant c can be treated as constant
- Using Lloyd-MAX quantizer may use the following bit allocation

Full scalar qunatizer

# of transmit	2	3			4					
Givens matrix	G1	G1	G2	G3	G1	G2	G3	G4	G5	G6
theta	2	2	2	2	2	2	2	2	2	2
c	2	1	1	1	1	1	1	1	1	1
Bit allocation to Givens	4	3	3	3	3	3	3	3	3	3

Figure 24

- The bit allocation may be used for partial scalar quantizer
- One solution includes using a 1 bit or zero bit for parameter c and using a differential 1-bit for parameter theta
- One approach includes using less bits or zero bit for the non significant Givens parameters

Partial scalar qunatizer

# of transmit	2	3			4					
Givens matrix	G1	G1	G2	G3	G1	G2	G3	G4	G5	G6
theta	2	2	1	1	2	2	1	1	1	1
c	2	1	0	0	1	1	0	0	0	0
Bit allocation to Givens	4	3	1	1	3	3	1	1	1	1

Figure 25

MIMO Configuration	**2x2**	**3x1**	**3x2**	**3x3**	**4x1**	**4x2**	**4x3**	**4x4**
# of spatial streams	2	1	2	3	1	2	3	4
# of parameters	1	2	3	3	3	5	6	6
Full Scalar	4	3	9	9	9	15	18	18
1-bit differential theta 1-bit for c	2	2	6	6	6	10	12	12
Hausholder	**4**	**4**	**9**	**9**	**11**	**11**	**15**	**15**

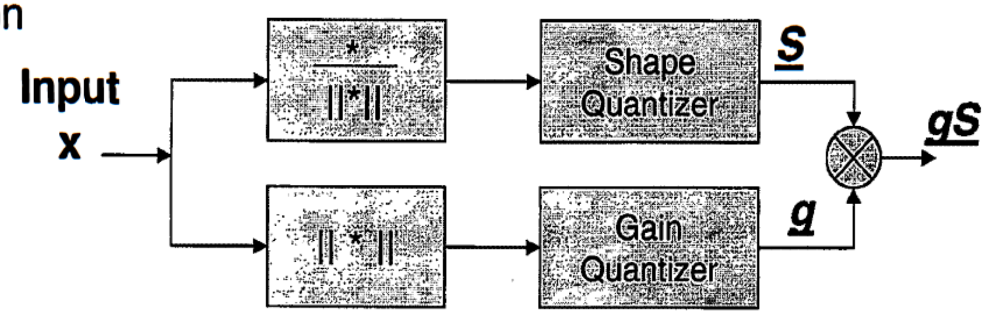
MIMO Configuration	**2x2**	**3x1**	**3x2**	**3x3**	**4x1**	**4x2**	**4x3**	**4x4**
# of spatial streams	2	1	2	3	1	2	3	4
# of parameters	1	2	3	3	3	5	6	6
Full Scalar	4	3	9	9	9	15	18	18
1-bit differential theta 1-bit or zero bit for c	2	2	4	4	5	7	9	9
Hausholder	**4**	**4**	**9**	**9**	**11**	**11**	**15**	**15**

Figure 26

- The individual Givens includes an unitary matrix
- The product of Givens is an unitary matrix
- The partial product of Givens is an unitary matrix
- Therefore we may first determine the truncated or full Givens expansion, the resulting of unitary matrix may be quantized by suing Grassmann sub-space packing
- The code book for quantization of unitary matrix may be considered as sub-space packing in Grassmann manifold
- Typical codebooks include:
  - Uniform distributed Grassmann space
  - Block circulant DFT

Figure 27

Encoding using shape and gain quantizer according to an embodiment of the invention



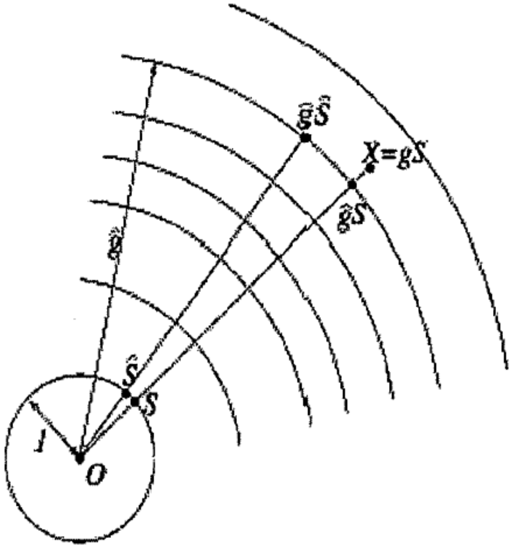


Figure 28

1. Given k element vector form the vector X → R^k
2. Compute $g=||X||$ and $S=X/g$
3. Use the gain codebook to quantize g as $\underline{g}$
4. Find I such that $\alpha_i =< \sin^{-1} x_k < \alpha_{i+1}$ and compute $h_i(S)==X/(||X||*(||X_L^j||-||X_L-X||)_+$
5. Find the nearest neighborhood $\underline{h}_i(S)$ to $h_i(S)$
6. Compute $h_i^{-1}(h_i(S))$ to identify the quantized shape $\underline{S}$
7. Compute the index $\underline{gS}$ and transmit

In accordance with an embodiment, Leech Lattice is used as a codebook

Alternatively, a trellis-coded quantizer can also be employed

Wrapped spherical vector quantizer

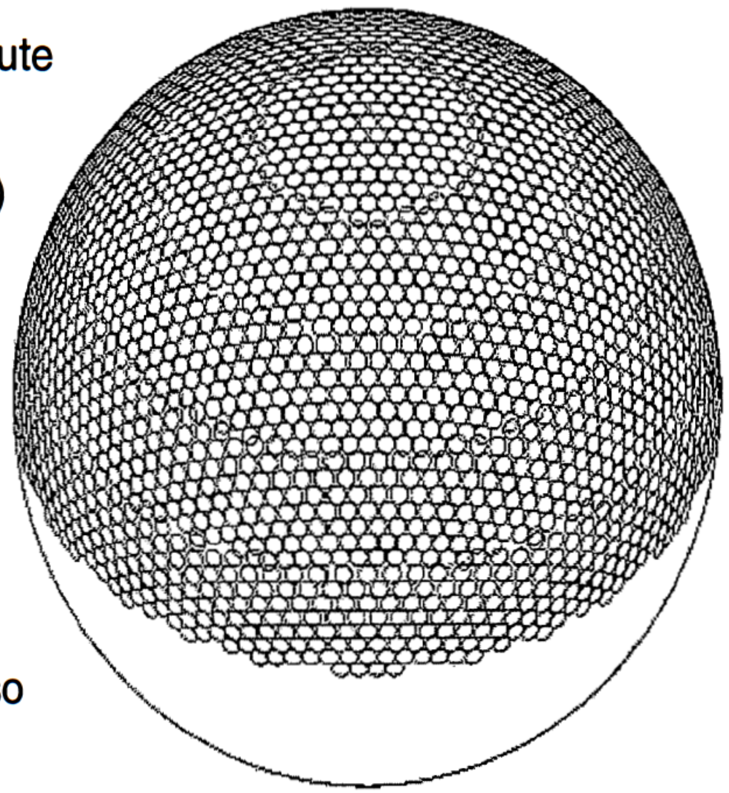


Figure 29

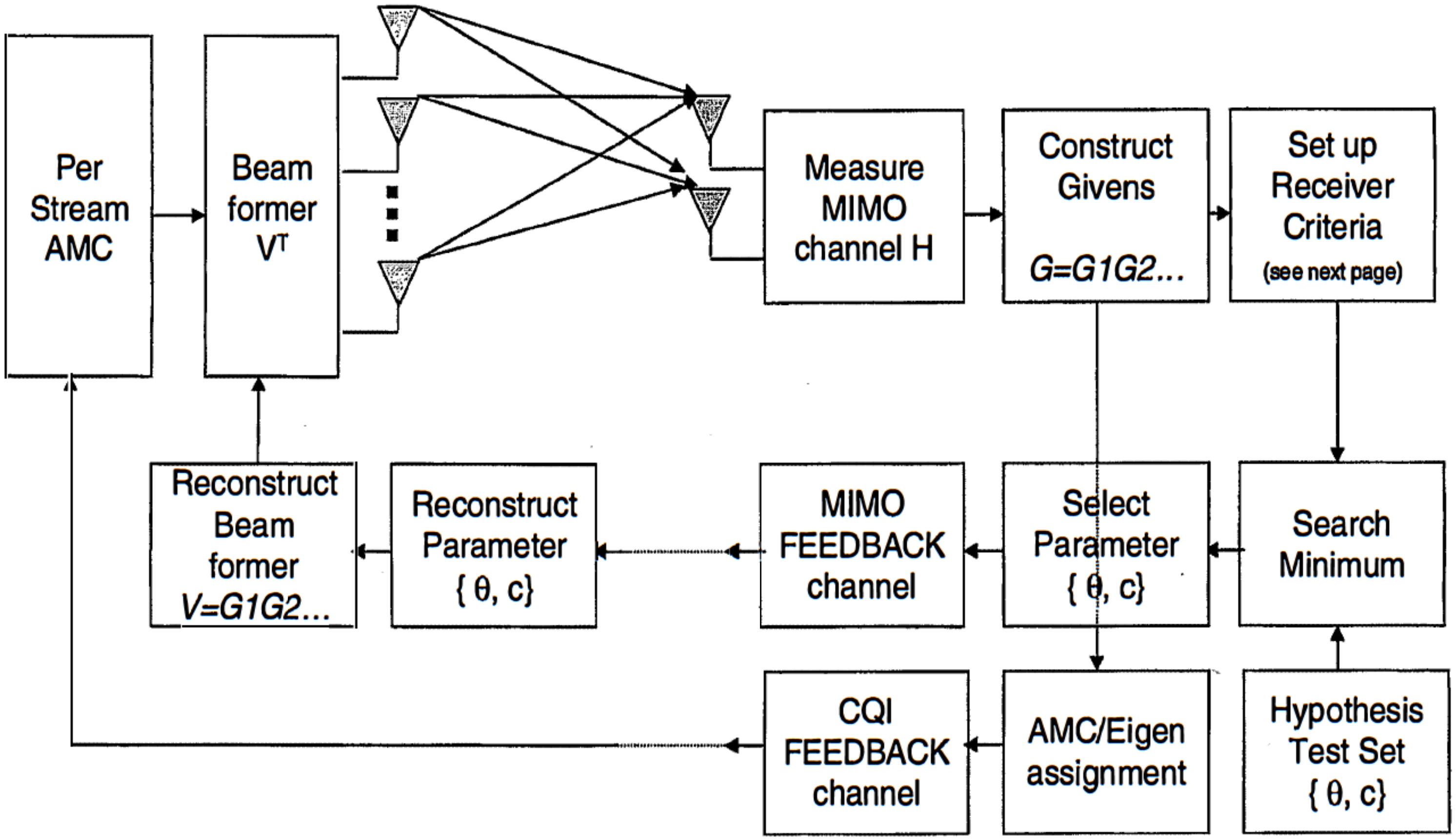

Per Stream AMC
Beam former V^T
Measure MIMO channel H
Construct Givens
$G=G1G2\ldots$
Set up Receiver Criteria
(see next page)
Search Minimum
Select Parameter $\{\theta, c\}$
MIMO FEEDBACK channel
Reconstruct Parameter $\{\theta, c\}$
Reconstruct Beam former
$V=G1G2\ldots$
Hypothesis Test Set $\{\theta, c\}$
AMC/Eigen assignment
CQI FEEDBACK channel

Figure 30

- In accordance with this embodiment of the invention channel fitting is based on criteria including the receiver criteria
- Based on the QoS requirement, the receiver determines the minimum feedback needed adaptively
- The determine process may including the following:
  - Determine the Givens truncation level
  - Based on the Scalar quantizer structure assign the parameter value
  - Perform combinatorial search of combinations
- One example search criterion may include receiver MSE
  - Others may include
    - Max SNR
    - Max Shannon capacity
    - True receiver operational process

$$l^{opt} = \arg \min_{l \in \{1,2 \ldots L\}} MSE\left\{ \frac{E_s}{N_o} tr\left(I_M + \frac{E_s}{N_o N_r} Q_l^H H^H H Q_l \right)^{-1} \right\}$$

Figure 31

- The feedback may send the Givens quantized values
- The feedback may use differential encoding method

Figure 32

- If the matrix is 4x4 then a determinantal polynomial may be used to provide a closed form solution

- For more than 4 transmit case, however, an iterative step may be required to find eigen-values, which reduces ultimately to finding the roots of the determinantal polynomial.

- For a symmetric or Hermitian matrix, Givens rotations or Householder may be used to convert the matrix initially to tridiagonal form, then the eigenvalues of this may be found by a similar iterative method using the 2x2 submatrices below the diagonal and a pivoting method.

- SVD may be iteratively computed by a Cholesky factorization and reverse order multiplication. if your asymmetric matrix is A, form
  - B = AA'
  - Decompose B as Cholesky factors B = L1.L1'
  - Multiply in reverse order: C = L1'.L1
  - Decompose C as new Cholesky factors C = L2.L2'
  - Multiply in reverse order: D = L2'.L2
  - Decompose D.
  - After approximately ten iterations the matrix should be diagonalized and the eigenvalues are on the diagonal of Ln

Figure 33

Givens decomposition is about 10% of SVD computing complexity

	Complexity		
	SVD	Givens	Givens/SVD
1	21	0	
2	168	12	7.14%
3	567	54	9.52%
4	1344	144	10.71%
5	2625	300	11.43%
6	4536	540	11.90%
7	7203	882	12.24%
8	10752	1344	12.50%

Hausholder+VQ is more complex

	Givens			Hausholder			
# of transmit antennas	Complex Division	Complex Multiply	Complex Add	Comparison	Complex Multiply	Complex Add	Complex Storage
3	3	30	30	32	259	160	32
4	4	56	56	64	771	672	64
6	6	132	132	256	3843	3744	256
8	8	240	240	1024	20227	20128	1024
12	12	552	552	16384	413443	413344	16384

Figure 34

- STTD/SM mode (MIMO feedback required)
  - Diversity Permutation
    - STTD/SM mode selection
    - Average CQI
  - AMC Band Permutation
    - STTD/SM mode selection
    - CQI of top X band (layer index + band index + CQI)
  - Antenna Grouping Based (for both diversity and AMC band permutation)
    - Group index and CQI
- SVD mode
  - Close loop and AMC band permutation
  - H matrix
    - Differential encoding
  - W vector
    - Differential encoding
  - V and CQI of top X layers
    - Differential encoding
  - Code book index of V and top X layers
    - Differential encoding

Figure 35

- Feedback Options
  - Option 1: Assign one or more dedicated fast feedback (CQICH) channel to provide MIMO channel feedback
    - Define a new MIMO_CQICH_Alloc IE
  - Option 2: Polling based feedback
    - Define MIMO Feedback Request message
    - Define MIMO Feedback Response message
  - Option 3: MSS autonomous MIMO feedback
    - Define MIMO feedback Response message
  - Option 4: MAC header based
    - Define MIMO feedback header format

Figure 36

- STTD/SM mode
  - Same as FDD
- SVD mode
  - Option-1
    - Same as FDD
  - Option-2
    - No explicit H or W or V is feedback
    - Design fast feedback channel so that
      - the sub-carriers (48 sub-carriers) are distributed across whole band in one or more OFDM symbol
      - At MSS side, the MSS transmits CQI payload
      - At BS side, the BS can decode CQI payload and at the same time, derives the channel information from the UL received CQI signal using some algorithm
  - Option-3
    - No explicit H or W or V is feedback
    - Design fast feedback channel so that preferably
      - the sub-carriers (48 sub-carriers) are distributed across whole band in one OFDM symbol
      - MSS transmits the CQI payload and a predetermined pilot pattern in a TDM fashion
        - » When a MSS sends CQI, the CQI payload is transmitted
        - » When a MSS transmits pilot, the pilot is directly mapped to 48 sub-carriers
      - BS can derive required channel info from the UL pilot

Figure 37

- MIMO_CQICH_Alloc IE
- MIMO feedback format
- MIMO Feedback Request message
- MIMO Feedback Response message
- MIMO feedback header

Figure 38

- CQICH may be used for the sounding of the UL MIMO channels in TDD
  - Reduces the overhead
  - Facilitates more accurate sub-band channel measurement,
  - Enough sampling density crossing the whole band should be achievable
- According to the symbol structure for PUSC, one UL sub-channel is constructed from 6 UL tiles, and each tile includes 4 sub-carriers crossing 3 symbols.
- The construction of MIMO CQICH
  - Partition the UL tile into 4 mini-tile
    - Each mini-tile includes one sub-carrier crossing 3 OFDM symbols
  - Concatenate 4 UL sub-channels
    - Total 24 (4x6) tiles and 96 (4x24) mini-tiles
  - Four MIMO CQICH channels are generated
    - One mini-tile is selected from each of the tile .

Figure 39

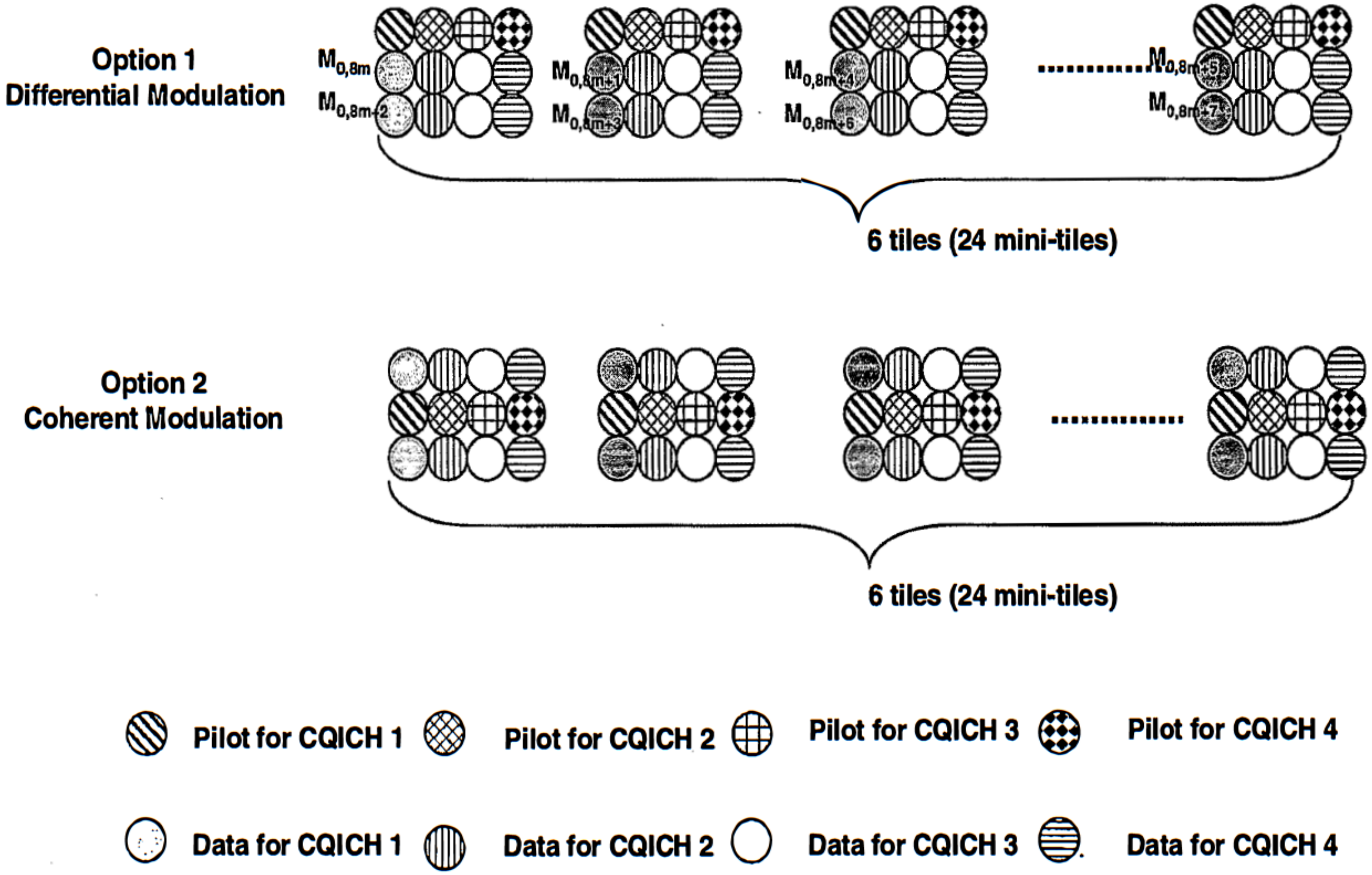

Option 1
Differential Modulation
$M_{0,8m}$
$M_{0,8m+2}$
$M_{0,8m+1}$
$M_{0,8m+3}$
$M_{0,8m+4}$
$M_{0,8m+6}$
$M_{0,8m+5}$
$M_{0,8m+7}$
6 tiles (24 mini-tiles)
Option 2
Coherent Modulation
6 tiles (24 mini-tiles)
Pilot for CQICH 1
Pilot for CQICH 2
Pilot for CQICH 3
Pilot for CQICH 4
Data for CQICH 1
Data for CQICH 2
Data for CQICH 3
Data for CQICH 4

Figure 40

- The construction of MIMO CQICH in accordance with an embodiment of the invention
  - Partition the UL tile into 2 mini-tile
    - Each mini-tile consists of two sub-carrier crossing 3 OFDM symbols
  - Concatenate 2 UL sub-channels
    - Totally 12 (2x6) tiles and 24 (2x12) mini-tiles
  - Two MIMO CQICH channels are generated
    - One mini-tile is selected from each of the tile
  - Two pilot patterns for two antennas

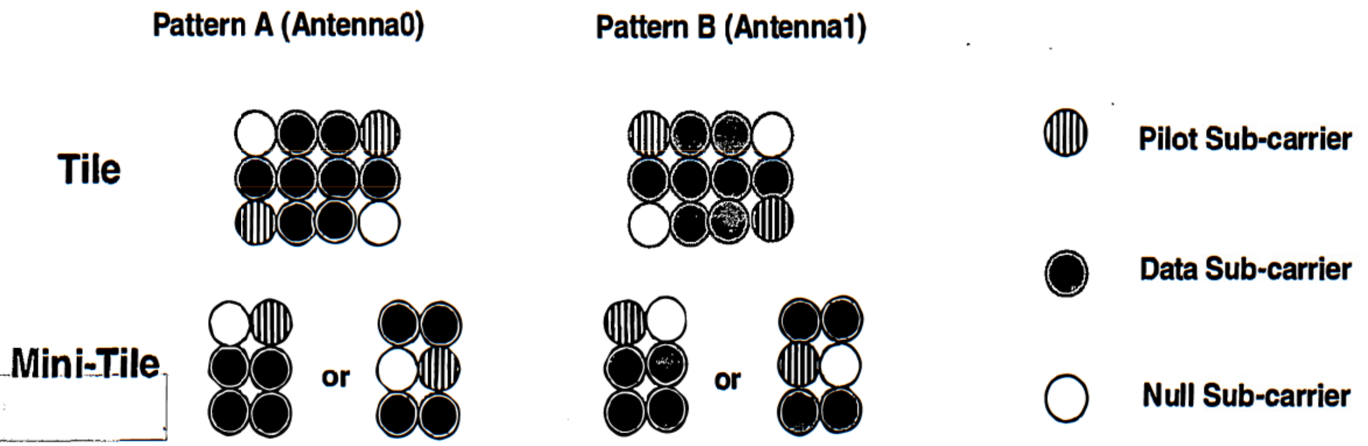


Figure 41

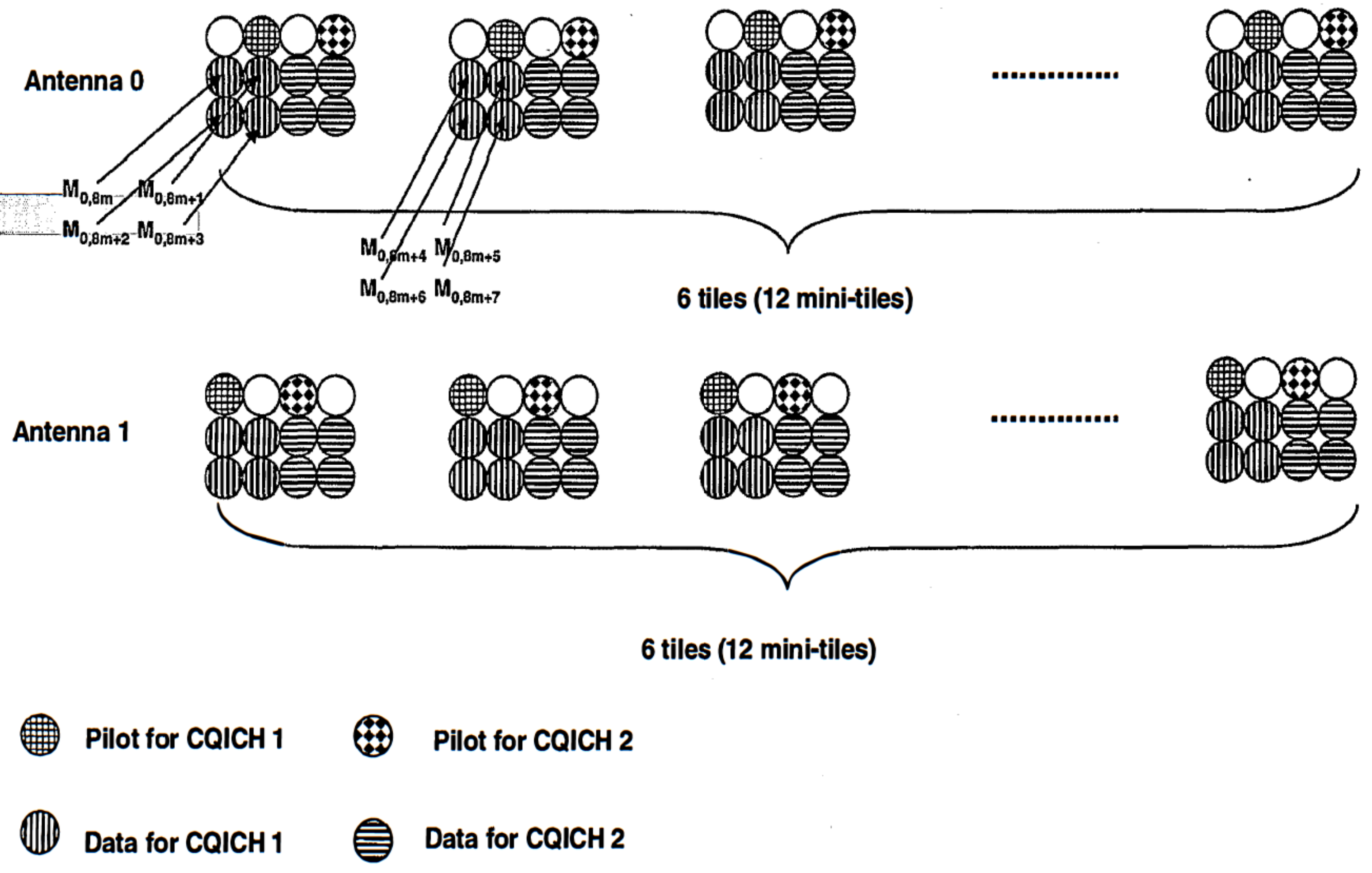

Antenna 0
$M_{0,8m}$
$M_{0,8m+1}$
$M_{0,8m+2}$
$M_{0,8m+3}$
$M_{0,8m+4}$
$M_{0,8m+5}$
$M_{0,8m+6}$
$M_{0,8m+7}$
6 tiles (12 mini-tiles)
Antenna 1
6 tiles (12 mini-tiles)
Pilot for CQICH 1
Pilot for CQICH 2
Data for CQICH 1
Data for CQICH 2

Figure 42

- Based on the optional symbol structure of PUSC, one UL sub-channel is constructed from 6 UL tiles, and each tile has 3 sub-carriers crossing 3 symbols.
- The construction of MIMO CQICH
  - Partition the UL tile into 3 mini-tile
    - Each mini-tile includes one sub-carrier crossing 3 OFDM symbols
  - Concatenate 4 UL sub-channels
    - Total of 24 (4x6) tiles and 96 (4x24) mini-tiles
  - Three MIMO CQICH channels are generated
    - One mini-tile is selected from each of the tile

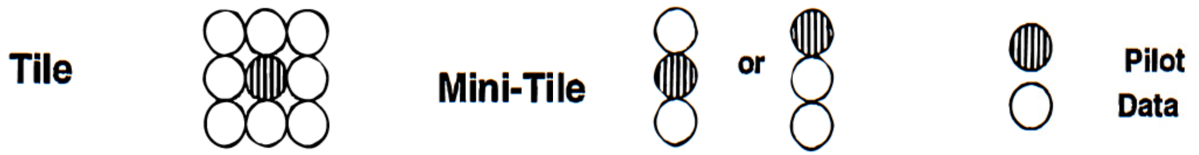


Figure 43

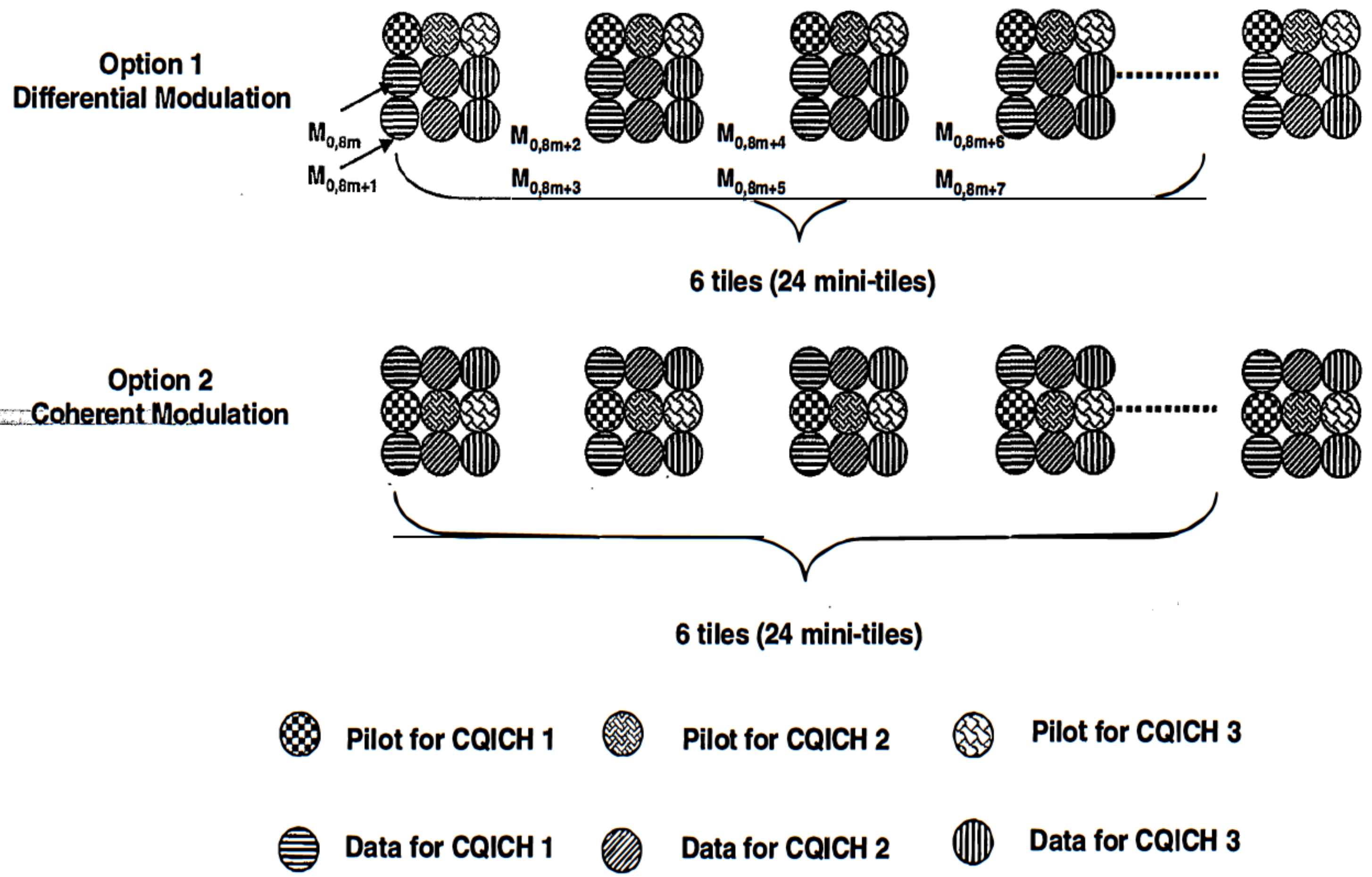

Option 1
Differential Modulation
$M_{0,8m}$
$M_{0,8m+1}$
$M_{0,8m+2}$
$M_{0,8m+3}$
$M_{0,8m+4}$
$M_{0,8m+5}$
$M_{0,8m+6}$
$M_{0,8m+7}$
6 tiles (24 mini-tiles)
Option 2
Coherent Modulation
6 tiles (24 mini-tiles)
Pilot for CQICH 1
Pilot for CQICH 2
Pilot for CQICH 3
Data for CQICH 1
Data for CQICH 2
Data for CQICH 3

Figure 44

- The construction of MIMO CQICH in accordance with an embodiment of the invention
  - Partition the UL tile into 3 mini-tile
    - Each mini-tile includes three sub-carrier crossing two OFDM symbols
  - Concatenate 4 UL sub-channels
    - Totally 12 (4x3) tiles and 36 (3x12) mini-tiles
  - Three MIMO CQICH channels are generated
    - One mini-tile is selected from each of the tile
  - Two pilot patterns for two antennas

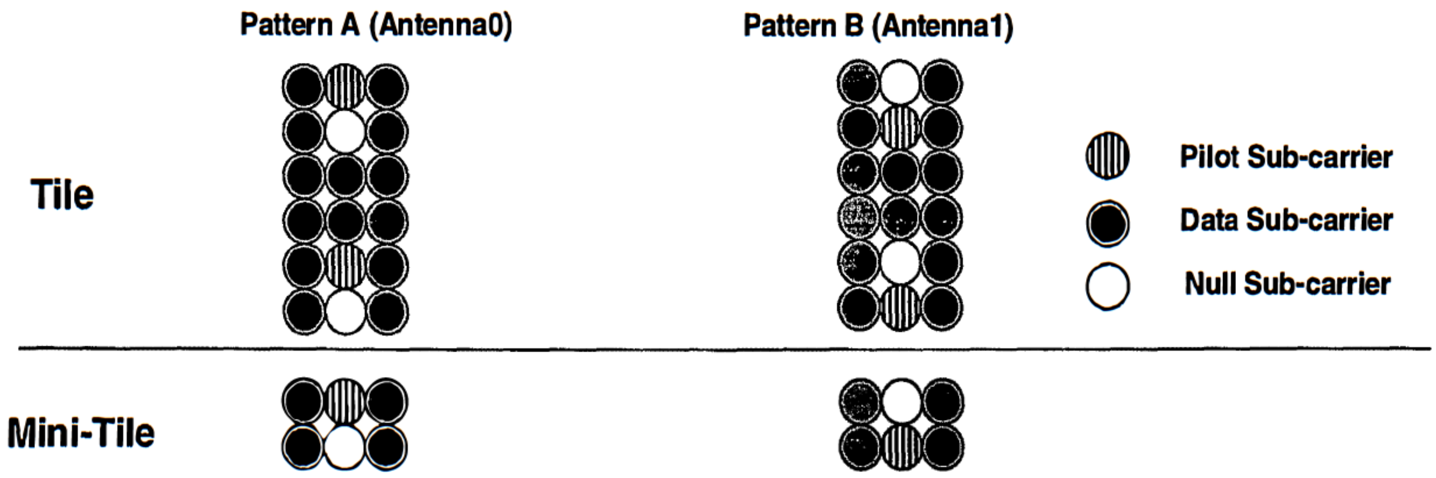


Figure 45

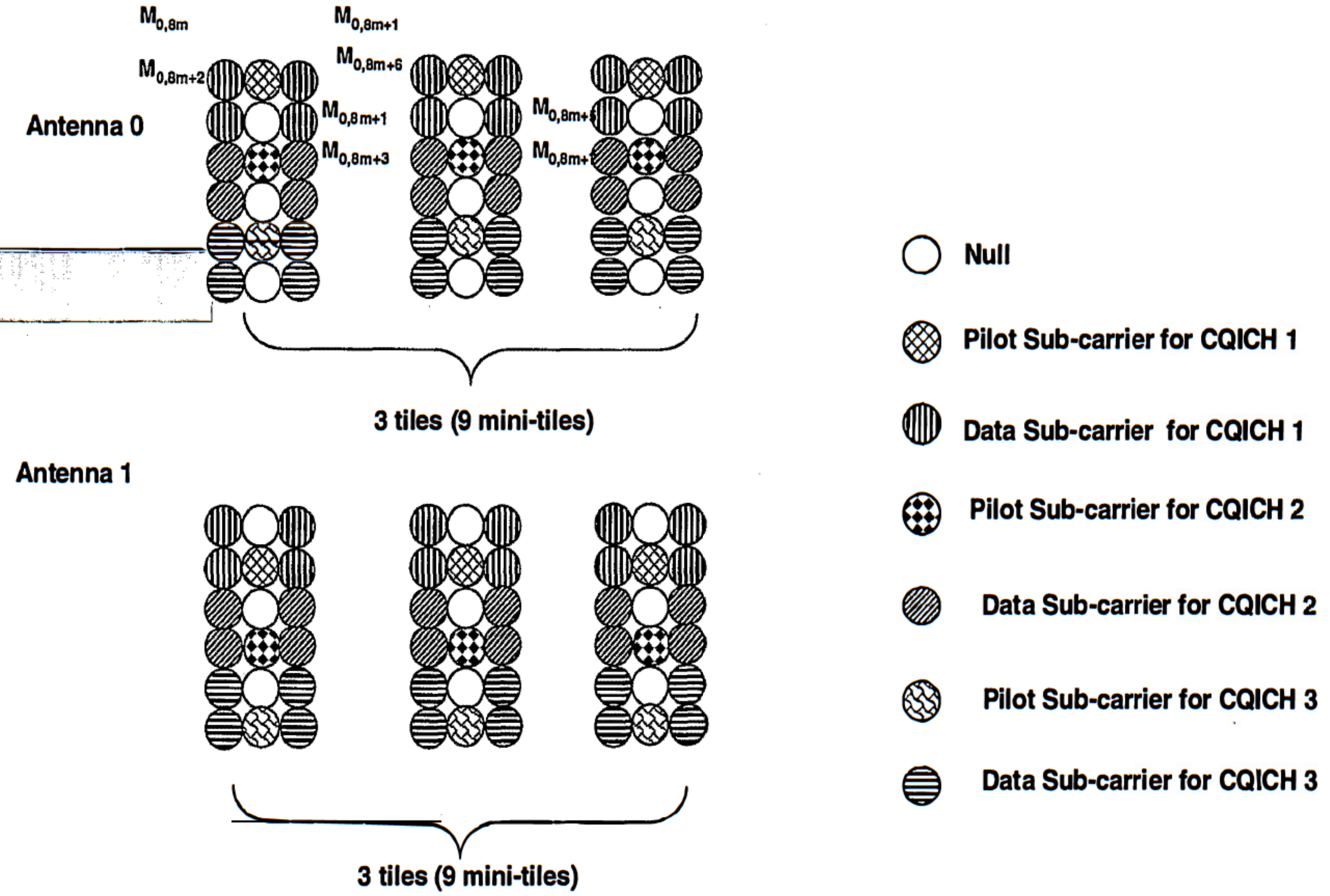

$M_{0,8m}$
$M_{0,8m+2}$
$M_{0,8m+1}$
$M_{0,8m+6}$
$M_{0,8m+1}$
$M_{0,8m+3}$
$M_{0,8m+}$
$M_{0,8m+}$
Antenna 0
3 tiles (9 mini-tiles)
Antenna 1
3 tiles (9 mini-tiles)
Null
Pilot Sub-carrier for CQICH 1
Data Sub-carrier for CQICH 1
Pilot Sub-carrier for CQICH 2
Data Sub-carrier for CQICH 2
Pilot Sub-carrier for CQICH 3
Data Sub-carrier for CQICH 3

Figure 46

- Since the pilot sub-carriers and the data sub-carriers are unchanged in each CQICH channel compared to the regular sub-channel, the same modulation scheme defined in the current standard may be applied. (Including, for example, the modulation method for FAST_FEEDBACK channels).
- Base station can obtain enough channel response samples after accumulating MIMO CQICH for N frames
  - For PUSC and optional PUSC, N=4
  - For 2-antenna PUSC and 2-antenna optional PUSC, N=8

Figure 47

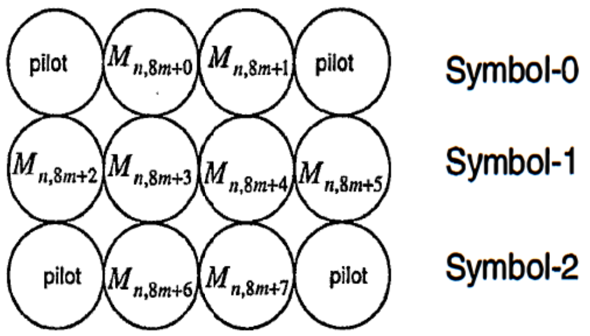
- The mini tile modulation includes

Vector index	$M_{n,8m}$ $M_{n,8m+1}$
0	P0, P1
1	P1,P0

$$P0 = \exp(j \cdot \frac{\pi}{4}),$$

$$P1 = \exp(j \cdot \frac{3\pi}{4}),$$

Figure 48



$$\overbrace{\hspace{10em}}^{M_{n,8m+7}}$$

Vector index	$M_{n,8m}$ $M_{n,8m+1}$ $M_{n,8m+7}$
0	P0, P1, P2, P3, P0, P1, P2, P3
1	P0, P3, P2, P1, P0, P3, P2, P1
2	P0, P0, P1, P1, P2, P2, P3, P3
3	P0, P0, P3, P3, P2, P2, P1, P1
4	P0, P0, P0, P0, P0, P0, P0, P0
5	P0, P2, P0, P2, P0, P2, P0, P2
6	P0, P2, P0, P2, P2, P0, P2, P0
7	P0, P2, P2, P0, P2, P0, P0, P2

$P0 = \exp(j \cdot \frac{\pi}{4})$,

$P1 = \exp(j \cdot \frac{3\pi}{4})$,

$P2 = \exp(-j \cdot \frac{3\pi}{4})$,

$P3 = \exp(-j \cdot \frac{\pi}{4})$

Figure 49

Matrix-A transmission

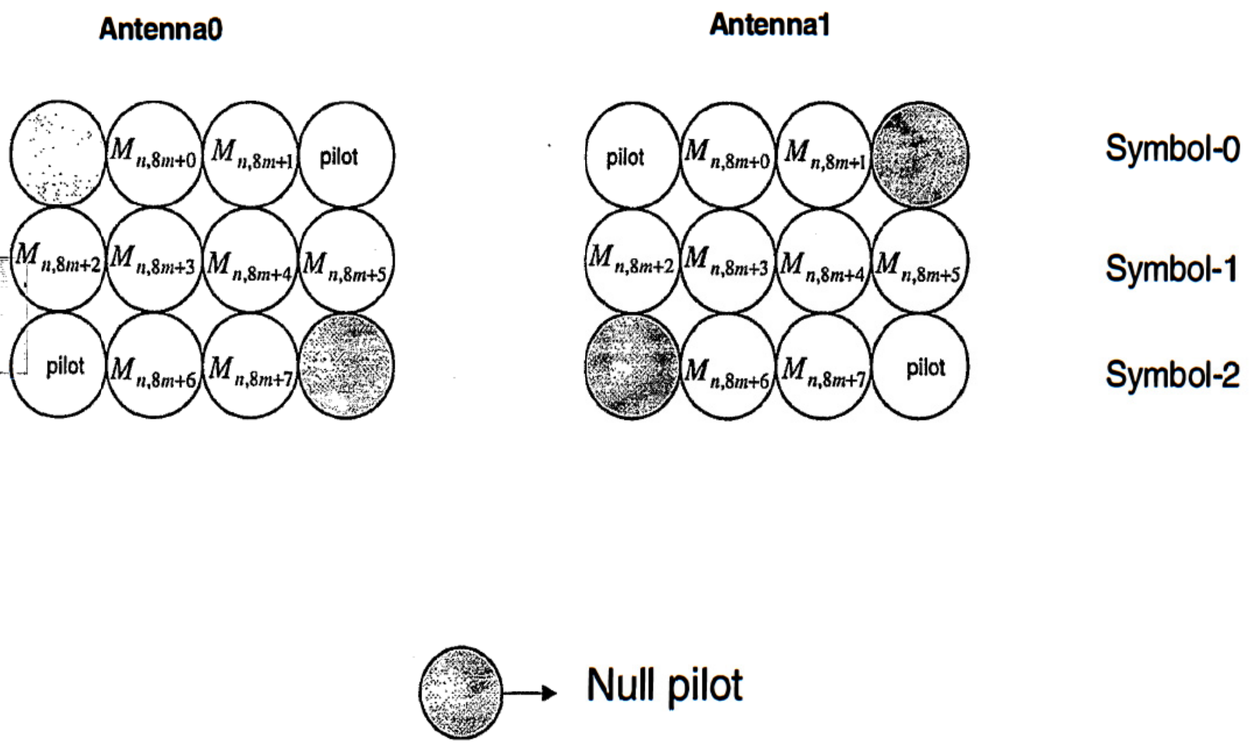


Figure 50

Matrix-B transmission

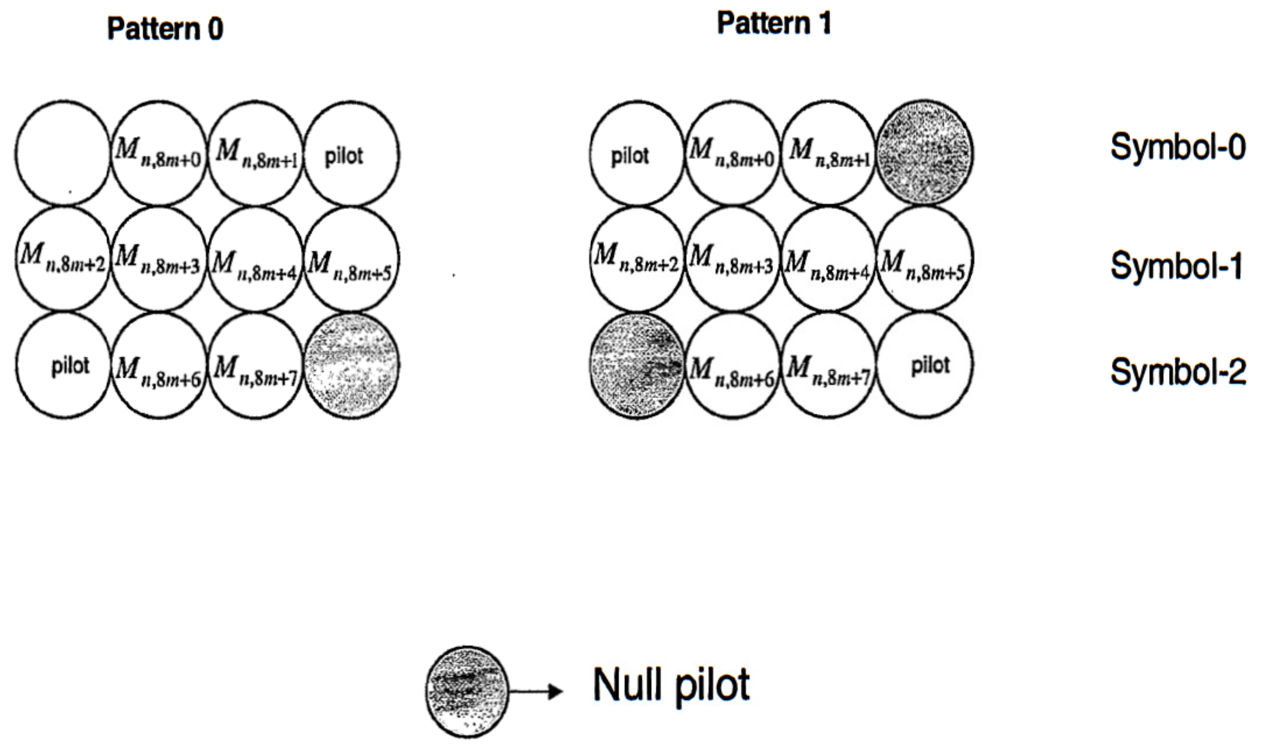


Figure 51

- For mobile MIMO channel the channel matrix may be time-varying

Time-0 → $H_0 = U_0 D_0 V_0'$

Time-1 → $H_1 = U_1 D_1 V_1'$

- The beam forming matrix V_0 sent to the transmitter may already be old
- However, the receiver may still be able to compute the latest receiver beam forming matrix U_0

$$U_1' y = U_1' U_1 D_1 V_1' V_0' s + U_1' n = D_1 V_1' V_0' s + n$$

- This may prevent the ageing impact at receiver side , the ageing impact will cause the inter-antenna interference

Figure 52

- Prediction of in the V-Space in accordance with an embodiment of the invention

$$U_1' y = U_1' U_1 D_1 V_1' V_0' s + U_1' n = D_1 V_1' V_0' s + n$$

- Use the advanced receiver such as MMSE or MLD to suppress inter-beam interface

Figure 53

- For pre-coded pilot, the equivalent channel becomes

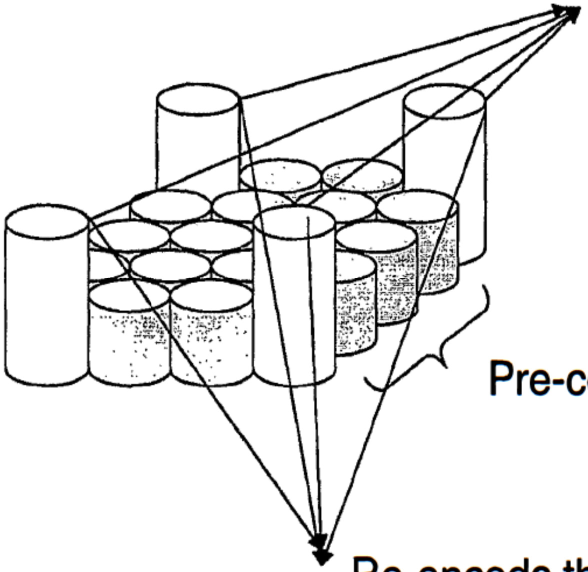
$$G = HW$$

- The feedback beam-former W may be computed from the channel H
- Two arrangements may be made:
  - Pre-code the scattered pilot, to recover the channel H by

$$H = GW'(WW')^{-1}$$

  - In accordance with this embodiment of the invention pilot is not pre-coded as the equivalent channel can be generated by each user
    - The advantages of this approach is to allow the other users to share the same scattered pilot for channel estimation

Figure 54



Non pre-coded channel H for

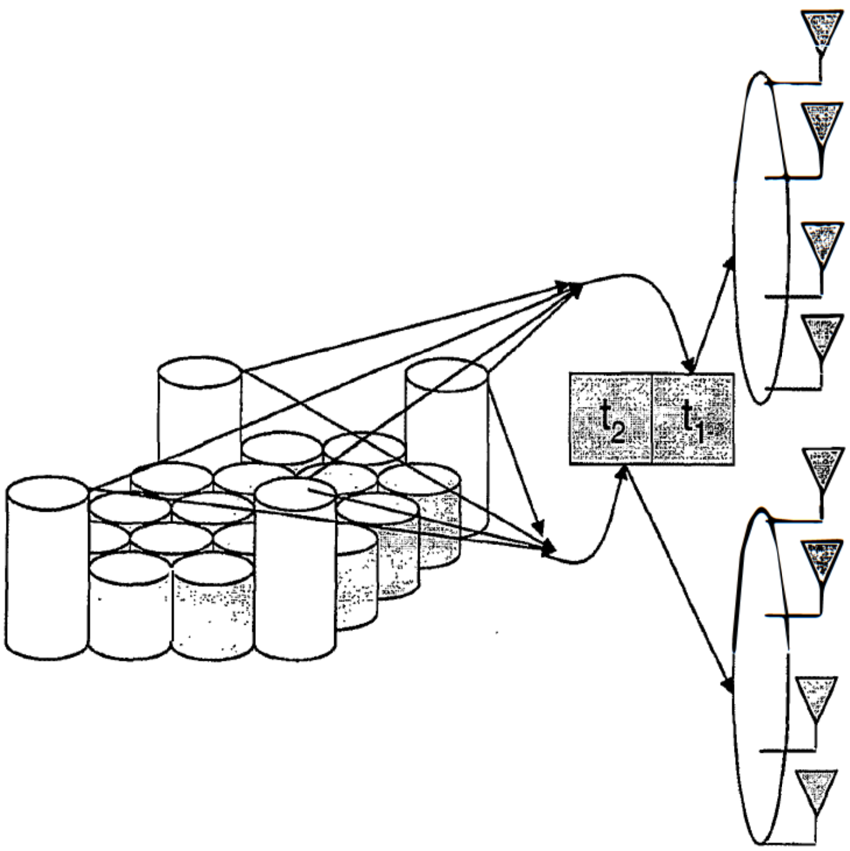
1. current H analysis and future feedback
2. Other user (including non-MIMO) to assist channel interpolation

Pre-coded data

Re-encode the non pre-coded channel H for

1. Coherent demodulate current ore-decode data

Figure 55



Increase pre-coded antenna array

1. Reduce the pilot sampling density in time or frequency
2. For mobility case, keep the time density, reduce the density in frequency domain
    1. For band AMC, it is preferable to select the most flat part of the band or use larger FFT size
    2. Interlace antenna pilot mapping
3. For nomadic case keep the frequency density reduce the density in time domain
    1. block antenna pilot mapping

Figure 56

- The cross-correlation of the codeword has a block circulant structure
- The diagonal rotation matrix Q is defined as:

$$Q=\begin{bmatrix} e^{j\frac{2\pi}{L}u_1} & & 0 \\ & \ddots & \\ 0 & & e^{j\frac{2\pi}{L}u_{l1}} \end{bmatrix} \Rightarrow U=[u_1 \ \cdots \ u_L]$$

- Matrix P$_1$ is selected from sub-matrixes of DFT matrix as $P_1=[d_{c_1} \ \cdots \ d_{c_{N_l}}]$

$$(D_{N_l})_{mxn}=\begin{bmatrix} e^{j\frac{2\pi}{N_l}(m-1)(n-1)} \end{bmatrix}_{mxn} \Rightarrow D=[d_1 \ \cdots \ d_{N_l}]$$

- The code book can be constructed as:

$$P_l=Q^l P_1 \qquad l=2,3,\ldots L$$

Figure 57

- The code book is optimized by choosing column indexes of DFT matrix:

$$c = \lfloor c_1 \quad \cdots \quad c_{M_l} \rfloor$$

- The code book is optimized by choosing rotation matrix *Q* indexes

$$u = \lfloor u_1 \quad \cdots \quad c_{N_l} \rfloor$$

Figure 58

- By exhaustive search of the code book we have

$$l^{opt} = \arg \min_{l \in \{1,2 \ldots L\}} MSE \left\{ \frac{E_s}{N_o} tr \left(I_M + \frac{E_s}{N_o N_r} P_l^H H^H H P_l \right)^{-1} \right\}$$

Figure 59

The **V** matrix is quantized column by column and recursively.

<u>**STEP-0**:</u> Denote the beamforming matrix as

$$\mathbf{V} = \begin{bmatrix} v_{11} & v_{12} & v_{13} \\ v_{21} & v_{22} & v_{23} \\ v_{31} & v_{32} & v_{33} \\ v_{41} & v_{42} & v_{43} \end{bmatrix}.$$

<u>**STEP-1**:</u> Quantize the first column of **V** denoted as $\mathbf{v}_1$ as follows.

$$\hat{\mathbf{v}}_1 = \arg\max_{\mathbf{u}\in C_1} \left\| \mathbf{u}^H \mathbf{v}_1 \right\|$$

where C_1 is a codebook containing unit 4-vectors for quantization. $\hat{\mathbf{v}}_1$ has the maximum inner product among all unit vectors in the codebook.

<u>**STEP-2**:</u> Compute Householder reflection matrix as follows

$$\mathbf{F}_1 = \mathbf{I} - \frac{2}{\left\|\mathbf{w}_1\right\|^2}\mathbf{w}_1\mathbf{w}_1^H,$$

Figure 60

where ϕ_1 is the phase of v_{11}.

$$\mathbf{F}_1\mathbf{V} = \begin{bmatrix} e^{j\phi_1} & 0.0 \quad 0.0 \\ \begin{matrix} 0.0 \\ 0.0 \\ 0.0 \end{matrix} & \underbrace{\begin{bmatrix} \hat{v}_{11} & \hat{v}_{12} \\ \hat{v}_{21} & \hat{v}_{22} \\ \hat{v}_{31} & \hat{v}_{32} \end{bmatrix}}_{\mathbf{V}_2} \end{bmatrix},$$

where two properties are employed to get the result, i.e. $\hat{v}_{11}$ *is real and the unitary property of* **V**. *Since both* $\mathbf{F}_1$ *and* **V** *are unitary,* $\mathbf{V}_2$ *is unitary. From STEP-2, we see that the size of* $\mathbf{V}_2$ *is 3 by 2 and it is reduced from that of* $\mathbf{V}_1$ *by one on both row and column dimensions.*

STEP-3: Quantize the first column of $\mathbf{V}_2$ denoted as $\mathbf{v}_2$, using another codebook of unit 3-vectors, whose first element of each codeword is real.

STEP-4: Construct a Householder reflection matrix $\mathbf{F}_2$

STEP-5: Multiply $\mathbf{F}_2$ with $\mathbf{V}_2$ as follows.

$$\mathbf{F}_2\mathbf{V}_2 = \begin{bmatrix} e^{j\phi_2} & 0.0 \\ \begin{matrix} 0.0 \\ 0.0 \end{matrix} & \underbrace{\begin{bmatrix} \breve{v}_{11} \\ \breve{v}_{21} \end{bmatrix}}_{\mathbf{V}_3} \end{bmatrix}$$

Figure 61

The reconstruction of the beamforming matrix **V** is as follows:

STEP-0: Two vectors, $\mathbf{v}_3$ and $\mathbf{v}_2$, are reconstructed using the feedback quantization indexes and the corresponding 2-vector and 3-vector codebooks.

STEP-1: Compute a Householder matrix using the reconstructed $\hat{\mathbf{v}}_2$ as

$$\mathbf{F}_2 = \mathbf{I} - \frac{2}{\|\mathbf{w}\|^2}\mathbf{w}\mathbf{w}^H,$$

where $\mathbf{w} = \hat{\mathbf{v}}_2 - \mathbf{e}_1$ *and* $\hat{\mathbf{v}}_2$ *is the reconstructed 3-vector;* $\boldsymbol{F}_2$ *can be stored beforehand to reduce computation.*

STEP-2: $\mathbf{V}_2$ can be reconstructed as

$$\hat{\mathbf{V}}_2 = \mathbf{F}_2\begin{bmatrix} 1 & 0 \\ 0 & \hat{\mathbf{v}}_3 \\ 0 & \end{bmatrix}$$

Figure 62

STEP-3: we reconstruct the first column of V using the quantization index and compute a Householder matrix as

$$\mathbf{F}_1 = \mathbf{I} - \frac{2}{\|\mathbf{w}\|^2}\mathbf{w}\mathbf{w}^H,$$

where $\mathbf{w} = \hat{\mathbf{v}}_1 - \mathbf{e}_1$ *and* $\hat{\mathbf{v}}_1$ *is the reconstructed first column of* ***V***.

STEP-4: the beamforming matrix **V** is given by

$$\hat{\mathbf{V}} = \mathbf{F}_1 \begin{bmatrix} 1 & 0 & 0 \\ 0 & & \\ 0 & \hat{\mathbf{V}}_2 & \\ 0 & & \end{bmatrix}.$$

Figure 63

- The codebook is constructed such that the codeword vectors distribute on the n-dimension complex unit sphere as uniformly. Additionally, the first element of each codeword is set to be real for the next step.
- The Householder matrix can be computed and stored beforehand for small codebooks. Even in the case that there is no quantization error, the reconstructed matrix could be different from the original **V** by a global phase on each column and this is fine with closed loop MIMO.

Figure 64

- Pre-design the rotation matrix for 2 transmit antennas
- The ration matrix is parameterized
- The set parameterized rotation matrixes served as code book

$$V^{l}_{n_1,n_2} = \begin{bmatrix} e^{j\phi_{n2}} \cos\theta_{n_1} & -e^{j\phi_{n2}} \sin\theta_{n_1} \\ \sin\theta_{n_1} & \cos\theta_{n_1} \end{bmatrix}$$

$$\phi_{n_2} = \frac{2\pi n_2}{N_2}, n_2 = 0,1,\cdots N_2 - 1$$

$$\theta_{n_1} = \frac{2\pi n_1}{N_1}, n_1 = 0,1,\cdots N_1 - 1$$

Figure 65

- Based on the receiver criterion, exhaustive search the code book and maximize the given received based criterion to determine the best pre-code matrix

$$SNR^{r}{}_{n,i} = \left(h_{n,i}{}^{r}\right)^{H}\left(h_{n,j}{}^{r}\left(h_{n,j}{}^{r}\right)^{H} + \sigma^{2}I\right)^{-1} h_{n,i}{}^{r}$$

$$i, j = 2, i \neq j,$$

$$n = 0,1,\cdots N-1$$

$$V^{opt}{}_{n} = \arg \max_{l} \left(\min_{i} \left(SNR^{r}{}_{n,i}\right)\right)$$