Abstract: Methods are disclosed for improving communications on feedback transmission channels, in which there is a possibility of bit errors. One method comprises the steps of choosing multiple mappings of indices to channel states, estimating the effect on transmission quality of feedback errors for each of the mappings of indices to channel states, selecting a mapping of indices to channel states to reduce the effect of feedback errors; and transmitting feedback of channel state information from the receiver to the transmitter, the receiver representing a channel state using the index determined by the selected mapping of indices to channel states.
MITIGATION OF TRANSMISSION ERRORS IN MULTI ANTENNA SYSTEMS

TECHNICAL FIELD

BACKGROUND
[0002] One of the most promising solutions for increased spectral efficiency in high capacity wireless systems is the use of multiple antennas on fading channels. The fundamental issue in such systems is the availability of the channel state information (CSI) at transmitters and receivers. While it is usually assumed that perfect CSI is available at the receivers, the transmitter may only have partial CSI available due to the feedback delay and noise, channel estimation errors and limited feedback bandwidth, which forces CSI to be quantized at the receiver to minimize feedback rate.

SUMMARY
[0003] Methods are disclosed for improving communications on feedback transmission channels, in which there is a possibility of bit errors. The basic solutions to counter those errors are: proper design of the CSI vector quantizer indexing (i.e., the bit representation of centroid indices) in order to minimize impact of index errors, use of error detection techniques to expunge the erroneous indices and use of other methods to recover correct indices (see pending US patent application "Quantized channel state information prediction in multiple antenna systems", application number 11/852,206 published as US2009/0067529 and "Multi-tiered quantization of channel state information in multiple antenna systems" application no. 11/852,240 published as US2009/0067512.) The content of USSN 11/754,965, 11/852,240 and 11/852,206 are incorporated herein by reference where permitted by law.

[0004] There are provided further methods and apparatus for reducing the effect of errors in the feedback of channel state information from a receiver to a transmitter. In an embodiment, the method comprises the steps of choosing multiple mappings of indices to channel states, estimating the effect on transmission quality of feedback errors for each of the
mappings of indices to channel states, selecting a mapping of indices to channel states to reduce the effect of feedback errors, and transmitting feedback of channel state information from the receiver to the transmitter, the receiver representing a channel state using the codeword determined by the selected mapping of indices to channel states

[0005] These and other methods and apparatus are set out in the claims, which are incorporated here by reference

BRIEF DESCRIPTION OF THE FIGURES

[0006] Embodiments will now be described with reference to the figures, in which like reference characters denote like elements, by way of example, and in which

[0007] Fig 1 is a schematic diagram showing the division of the channel state space into Voronoi regions

[0008] Fig 2 shows the basic structure of a system for carrying out the proposed methods

[0009] Fig 3a shows a good mapping of indices to centroids

[0010] Fig 3b shows a bad mapping of indices to centroids

[0011] Fig 4 shows the general operation of an embodiment of an indexing optimization algorithm

[0012] Fig 5 shows the operation of the initialization phase of the exemplary indexing design algorithm of Fig 4

[0013] Fig 6 shows the operation of the optimization phase of the exemplary indexing design algorithm of Fig 4

[0014] Fig 7 shows an embodiment of the system operation with error-detecting codes

[0015] Fig 8 shows an embodiment of the system operation without error detecting codes

[0016] Fig 9 shows a more general embodiment of an indexing algorithm

DETAILED DESCRIPTION

[0017] In the typical CSI vector quantizer (VQ), the quantization of the channel vector space is performed as in Fig 1 the available space is tessellated by Voronoi regions 20 with corresponding centroids 22 that represent all vector realizations within each Voronoi region. The number of such regions (centroids) is defined by the number of available bits and each
centroid is assigned an index 23 with the binary representation of length equal to the number of available feedback bits. The indices can also be represented by arbitrary sequences of symbols, so long as each index is represented by a unique sequence of symbols, and the symbols can be transmitted by the feedback channel. When the receiver transmits its channel state information to the transmitter, it is the bits (or symbols) representing the centroid indices that are physically sent over the feedback channel. When the term "binary index" is used, one could substitute "the sequence of symbols representing the index". In the claims when a mapping of indices to channel states is mentioned, a mapping of symbol sequences to indices would serve the same purpose and so the claims should be construed to cover both.

[0018] All presented solutions can be used for both eigenmode and singular value codebooks in systems ranging from only one active receiver at a time to systems with multiple receivers being active simultaneously (where we define being active as receiving transmissions). The design of the feedback encoding solutions can be applied to quantized matrices of orthogonal eigenmodes, subsets of eigenmodes and scalar singular values as necessary. The following descriptions will be generic in form so that they can easily be applied to any type of CSI quantizing solution.

[0019] Figure 2 shows the basic structure of the system proposed in US patent application 11/754,965. The system works as follows:

1. Before the transmission epoch, each receiver 38 estimates 40 its channel matrix \( H \) for a feedforward channel 34 and uses this information to perform the singular value decomposition (SVD) 42 of the matrix.

2. The eigenmode and singular value components are separately quantized 44 using two codebooks \( V46 \) and \( D48 \), respectively.

3. The indices of the selected codewords are encoded 52, 54 and fed back 56, 58 to the transmitter 36 on a feedback channel 50.

4. The transmitter includes an indexer and optimizer 66 which uses all decoded 60, 62 indices 64 from all receivers in the system to choose 68, 70 the preselected linear modulation and power allocation matrices \( B \) and \( S \), respectively. The choice is based on a predefined set of rules (maximum fairness, throughput, for example).

5. The input signal 72 is modulated using the modulation 74 and power allocation 76
matrices, transmitted to the receiver over the feedforward channel 34, using antennas
32, and the transmitted modulated signal is processed 78 by the receiver.

[0020] The feedback channel 50 shown in Fig. 2 will inevitably suffer from the
transmission errors and the indices of the channel vectors reported by the receivers will be
erroneously decoded at the transmitter. Even if the feedback information is protected by
channel codes, in a multiple user scenario, it is possible that the interference will cause the
indices to be detected with errors, which will lower the system's throughput.

[0021] For example, in Fig. 1, during the first part of the actual vector trajectory 24, the
centroid index number 3 represented by bits 011 would be reported to the transmitter.
However, if for some reason, the second index bit would be recovered with an error, the
centroid index number 1 (represented by bits 001) would instead be received by the
transmitter, which would cause it to choose improper modulation matrices B and S (see
previous section).

[0022] The basic transmission of the feedback indices 23 may comprise the following
steps:

1. Selection of the indices 23 representing the centroids 22 closest to the actual channel
vectors.
2. *(Optional)* Adding error detection check bits to the binary representation of the
centroid indices.
3. *(Optional)* Adding channel error correction check bits.
4. Transmission of all the bits.
5. *(Conditioned on 3)* Performing channel decoding of the received bits.
6. *(Conditioned on 2)* Performing error detection of the received bits.
7. Reporting the received channel vector indices to the optimizer/indexer in Fig. 2.
8. *(Optional)* Reporting which indices contain errors to the optimizer/indexer in Fig. 2.

This step can use results from 6 or any alternative method as outlined later on.

[0023] Based on the above eight steps, the indexer will now be able to make decision on
the choice of modulation matrices for the next transmission epoch. Three exemplary
approaches to the problem are:

1. If error detection codes or any *alternative* error detection method is used and the base
station optimizer is aware of erroneous receiver indices, it may **discard** them and only use the correct ones in the optimization phase.

2. If error detection codes or any alternative error detection method is used and the base station optimizer is aware of erroneous receiver indices, it may **attempt to recover** them and use all received indices (correct and recovered) in the optimization phase.

3. If error detection is **not used** at all, the optimizer assumes that the received indices are very close to the actual transmitted indices and **use them as if they were all correct.**

[0024] A basic difference between methods 1, 2 and 3 lies in whether the error detection methods are used to detect problems in channel information indices fed back to the base station. If such methods are used, the transmitter may recognize which indices are incorrect and can take appropriate actions. If no error detection may be performed and the received indices are used 'as-is', the vector quantizer indexing **must be** properly designed as shown in Fig. 3a

[0025] The mapping of the indices to the centroids in a quantizer is a complex task that can influence the system's performance tremendously when errors in the feedback link are not negligible. Figs. 3a and 3b shows the situation, where the identical vector quantizer has a different mapping of indices 23 and the results of one bit error in the transmission of the centroid indices.

[0026] In Fig. 3a, the mapping was done in a way that ensured that one bit error in the last position of the index moved the centroid received at the transmitter not far from the actual one. In other words, the small Hamming distance of the difference between the actual and received indices of the centroid corresponds to the small distance 26 between the actual centroids. The centroid distance 2-6 function will be discussed further in the document.

[0027] In Fig. 3b, the small Hamming weight of index error does not correspond to the small centroid distance. In this case, a 1-bit error forces the centroid to move far away from the actual one, which may have a very negative influence on the system's performance.

[0028] The following algorithms are presented:

1. Design of the indexing for CSI MIMO vector quantizers.
2. Actual operation of the system using encoded feedback link with CSI MIMO
quantizers with or without error detection.

[0029] The algorithm for the design of the indexing can be carried out in any suitable computing device, including for example pen and paper. Typically the design will be carried out prior to the initialization of the MIMO system.

[0030] The following notation will be used:
- $V_k$ – the $k$th centroid in codebook $V$.
- $k, l$ – indices of centroids in codebook $V$.
- $d_{kl}$ – the distance between the centroids specified by indices $k$ and $l$.
- $d(k; e)$ – distance profile for centroid $k$ and a given number of bit errors $e$.
- $G_k P(e)$ – global distance profile for a given number of bit errors $e$.
- $i, j$ - binary indices of a codeword in a vector quantizer.
- $H_j$ – the Hamming distance between indices $i$ and $j$.
- $I$ – the number of iterations of the index optimization algorithm.
- TV – the length of the binary representation of centroid indices $k$.

[0031] It is assumed that the indexing design follows the design of the channel vector quantizer. Fusing any known method, for example the method shown in the patent application "Quantization of channel state information in multiple antenna systems" (US patent 11/754,965 pending) or the other US patent applications mentioned here. The input to the quantizer indexing algorithm is the distance matrix $D$ with number of rows and columns equal to the number of all centroids $V_k$ (with our notation the number of rows and columns is equal to $2^i$). The entries in the matrix are distances between the centroids - for example, the $k$th row and $l$th entry is given by $da$. In particular, the entries on the diagonal of the matrix are equal to 0. The methods used to calculate the distance matrix $D$ as well as the centroid distances are immaterial in this patent application. However, some of the methods to calculate the centroid distances for the matrix $D$ can be defined as follows:

1. $d_{kl}$ is the angle between the centroids $V_k$ and $V_l$.
2. $d_{kl}$ is the smaller of the angles between the centroids $V_k$ and $V_l$ and between the centroids $V_k$ and $-V_l$. 
3. $d_{kj}$ is the Euclidean distance between the centroids $V_t$ and $V$.
4. $di$ is the average system throughput loss when centroid $V_k$ is chosen instead of $V$.
5. $d_{ij}$ is the user system throughput loss when centroid $V_k$ is chosen instead of $V_i$.
6. Any other distance definition depending on the system design parameters

[0032] In addition to the distance metric $d_{kj}$, representing a distance between two specified quantizer centroids, a set of distance profiles, $d(k;e)$, and a global distance profile, $GDP(e)$, are used to represent the distance profile of the indexed quantizer. A distance profile $d(k;e)$ for a given centroid $k$ and a number of errors $e$ represents a set of numbers corresponding to the distances between all erroneous representations of the centroid $V_k$ and the actual centroid $V_k$. Assuming that $e$ errors appeared during the transmission of its corresponding index $l$. In other words,

$$d(k;e) = \{d_1, d_2, d_3, ..., d_{n_e} \},$$

where $n$ is the number of $e$-element subsets in JV-long binary representation of codebook indices and $d_{n_e}$ corresponds to distances $d_{ki}$ between the centroid $V_k$ and its erroneous version $V_k$ containing $e$ index errors.

[0033] Finally, to characterize the entire codebook, a global distance profile $GDP(e)$ is defined as the union of all distance profiles $d(k;e)$.

Indexing design algorithm.

[0034] Design of the indexing based on the distance matrix $D$ is performed using a heuristic algorithm operating in two phases: the initialization phase and optimization phase. Since the initialization phase of the algorithm depends on random initial choice of indices, it is recommended that both phases of the algorithm are repeated storing the index map after each optimization step for a given number of iterations / until the best solution has been found or the design constraint has been met. The general operation of the indexing design algorithm is shown in Fig. 4 and described below.

[0035] General algorithm:
1. In step 80, initialize iteration counter / and in step 82 the previous global distance profile $GDP_{prev/alls}$
2. In step 84, run the **Initialization phase** of the algorithm (see below).
3. In step 86, run the **Optimization phase** of the algorithm (see below).
4. In step 88, store index map and calculate the new global distance profile $GDP(e)$.
5. In step 90 compare $GDP(e)$ with $GDP_{prevous}$; in step 92 check if $GDP(e)$ improves $GDP_{prevous}$ and if so then in step 94 exchange $GDP_{prevous}$ with $GDP(e)$ and store the current index map.
6. In step 96 increase / by 1.
7. In step 98 if/ /go to 2.
8. In step 100, STOP.

**[0036]** **Initialization phase:**

1. In step 102, generate the distance matrix $D$; in step 104 initialize the lists of unassigned indices, centroids and processed entries in $D$.
2. In step 106, find the smallest unprocessed entry $<4/>0$ in the matrix $D$.
3. Mark the entry $d_{ki}$ as processed.
4. In step 108 search for centroids $V_k$ and $V_i$ corresponding to $d_{ki}$ in step 110 check if any indices have been assigned to either centroid. If neither centroids $V_k$ nor $V_i$ corresponding to $d_{ki}$ have been assigned any indices / or/ in step 112 (a-c), step 118 (d-e) and step 120 (f):
   a) Choose a random index / from the list of the unused indices.
   b) Assign the index / to the centroid $V_k$.
   c) Mark the /th entry in the list of used indices list as taken.
   d) Choose a random index/ from the list of the unused indices in such a way that the corresponding $H_{ij}$ is minimized.
   e) Assign the index / to the centroid $V_i$.
   f) Mark the /th entry in the list of used indices list as taken, and $V_i$ has an index assigned to it in the list of used centroids.
5. In step 114, check if only one of the centroids $V_k$ or $V$ have been assigned an index, and if so in step 118 (a-b) and step 120 (c):
   a) Choose a random index/ from the list of the unused indices in such a way that
$H_{\eta}$ is minimum, where it is assumed (step 116) that $l$ is the binary index of the already indexed centroid.

b) Assign the index $j \neq l$ the unassigned centroid.

c) Mark the $j$th entry in the list of used indices as taken, and mark the unassigned centroid as assigned.

6. If both centroids $V_k$ or $V_l$ have been assigned an index, go to 7.

7. In step 122, if there are still unassigned indices, go to 2.

8. In step 124, STOP.

[0037] The operation of the initialization phase is presented in Fig. 5.

[0038] After the completion of the initialization phase, all centroids $V_k$ in the codebook $V$ have been assigned the binary indices $l$, with the majority of smallest distances $d_{ii}$ in matrix $D$ coupled to the binary indices $l$ and $j$ with small Hamming distances. However, the initialization phase can only reach locally optimum solutions and, in the next step, an improved solution is iteratively searched for.

[0039] **Optimization phase:**

1. In step 130, generate the distance matrix $D$ and initialize the global distance profile $GDP(e)$.

2. In step 132, initialize the list of processed entries in $D$.

3. In step 134, set the previous global error distance as $(GDP)_{previous} = GDP(e)$.

4. In step 136, find the smallest unprocessed entry $d_{lp} \neq 0$ in the matrix $D$, and mark it as processed.

5. In step 138, find the binary indices $l$ and $j$ assigned to the centroids $k$ and $l$. Choose whether to swap them as follows:

   a) In step 140, calculate the global distance profile $GDP_{mvm}^{V}(e)$ with mapping of centroid $V_k$ to binary index $l$ and centroid $V_l$ to binary index $j$.

   b) In step 142 and 144, calculate the global distance profile $GDP_{S&Koppe}^{V}(e)$ with mapping of centroid $V_k$ to binary index $l$ and centroid $V_l$ to binary index $j$.

   c) In step 146 choose the mapping corresponding to better global distance profile from 6a) and 6b) and in step 148 assign the indices of centroids accordingly.

6. In step 150, check the list of the processed entries $d_{kl}$ and if there are still
7. In step 152, calculate the $GDP(e)$ with the current mapping of centroids and indices. If it is better than $\langle DP \rangle_{\text{prev}}$, then go to 2.

8. In step 154, if there are no improvements over $GDP_{\text{prev}}$, STOP.

[0040] The operation of the optimization algorithm is presented in Fig. 6.

[0041] The optimization phase iteratively searches for better mapping between centroids and indices by swapping the binary representation of the closest pairs. After each such swap, the global distance profile for swapped mapping is compared to the unswapped mapping and the globally better solution is chosen. The algorithm is repeated iteratively through all centroids and stops when no improvement can be achieved by consecutive swapping of the indices.

[0042] A more general version of this approach to indexing is shown in Fig. 9. In Fig 5, pairs of centroids (that is, channel states representing a region of channel state space for purposes of quantization) near one another in terms of the chosen distance measure are chosen and are assigned indices also near one another in Hamming distance, Hamming distance being a proxy for the probability of one index being mistakenly received as another (the less the distance, the more likely they will be confused). Since the feedback bandwidth is limited, there will have to be indices near one another in Hamming distance. The effect of feedback errors is reduced if such nearby indices are assigned to nearby channel states, so as to reduce the effect on transmission quality if they are mistaken for one another. Hence the initialization phase depicted in Fig. 5 can be regarded as choosing multiple mappings of indices to channel states in step 220 (the different possible assignments of indices to a pair of channel states), estimating the effect of feedback errors of each in step 222 (using Hamming distance as a proxy in this case), and selecting one in step 224 (in this case one with the minimum Hamming distance) so as to reduce the effect of feedback errors. Similarly the optimization phase shown in Fig. 6 includes choosing multiple mappings of indices to channel states in step 220 (in this case differing from one another by the swapping of pairs of indices), estimating the effect of feedback errors of each mapping (in this case using the global distance profile), and selecting a mapping to reduce the expected effect of feedback errors (by choosing the one with the best global distance profile in this case). No matter how the
mapping is selected, it is used in step 226 to send feedback of information concerning a channel state from a receiver to a transmitter, the receiver representing the channel state using the index mapped to the exemplary state (e.g. centroid) for the region of channel state space in which the channel state lies.

System operation with error detection in the feedback link

[0043] If the system uses error detecting codes in the feedback link, its operation can be summarized as follows:

1. In step 160, initialize transmission epoch to $t=l$.
2. In step 162, each receiver estimates its channel matrix $H[Y]$.
3. In step 164, each receiver performs the vector quantization of the channel state information.
4. In step 166, the channel state information indices are encoded using error detecting code (such as CRC).
5. (Optional) In step 168, the channel state information indices with the error-detection redundancy are encoded using error correcting code (such as convolutional or turbo codes).
6. In step 170, the encoded channel state information indices are fed back to the transmitter.
7. (Conditional on 5) In step 172, the received channel state information indices are decoded in a channel decoder that attempts to correct possible channel transmission errors.
8. In step 174, the decoded indices are checked by an error-detecting decoder.
9. In step 176, the receiver counts the number of erroneously decoded indices.
10. Depending (in step 178) on the implementation, the receiver may then:
    a) In step 180, expurgate the erroneous indices, if there are still enough indices for optimization process, and process only the remaining ones
    b) In step 184, ignore the errors and use the erroneous indices.
    c) In step 182, regenerate the erroneous indices, for example, by using the
channel prediction techniques from pending US patent application "Quantized channel state information prediction in multiple antenna systems" 11/852,206.

11. In step 186, the transmitter performs the selection of active users using any method (maximum fairness, maximum throughput etc.) and chooses the corresponding modulation matrices.

12. The signal is transmitted to the selected active receivers.

13. In step 188, increase transmission epoch as t=t+1.

14. Go to 2.

[0044] The operation of the algorithm is presented in Fig. 7.

System operation without error detection in the feedback link

[0045] If the system uses no error detecting codes in the feedback link, its operation can be summarized as follows:

1. In step 190, initialize transmission epoch to t=1.

2. In step 192, each receiver estimates its channel matrix H[Z].

3. In step 194, each receiver performs the vector quantization of the channel state information.

4. (Optional) In step 196, the channel state information indices with the error-detection redundancy are encoded using error correcting code (such as convolutional or turbo codes).

5. In step 198, the encoded channel state information indices are fed back to the transmitter using the method described in previous sections.

6. (Conditional on 4) In step 200, the received channel state information indices are decoded in a channel decoder that attempts to correct possible channel transmission errors.

7. If (step 202) the index error detection is possible using alternative methods, for example, channel prediction techniques such as the one presented in the pending US patent application "Quantized channel state information prediction in multiple antenna systems" 11/852,206, the transmitter may:

   a. In step 206, expurgate the erroneous indices if there are still enough indices for
optimization process,
b. In step 204, regenerate the erroneous indices using, for example, channel prediction techniques.
8. If (step 202) the index error detection is impossible, in step 208 the receiver uses the received indices as correct ones,
9. In step 210, the transmitter performs the selection of active users using any method (maximum fairness, maximum throughput etc.) and chooses the corresponding modulation matrices.
10. The signal is transmitted to the selected active receivers.
11. In step 212, increase transmission epoch as $t=t+l$.
12. Go to 2.

[0046] The operation of the algorithm is presented in Fig. 8.

[0047] Immaterial modifications may be made to the embodiments described here without departing from what is covered by the claims. In the claims, the word "comprising" is used in its inclusive sense and does not exclude other elements being present. The indefinite article "a" before a claim feature does not exclude more than one of the feature being present. Each one of the individual features described here may be used in one or more embodiments and is not, by virtue only of being described here, to be constituted as essential to all embodiments as defined by the claims.
What is claimed is

1 A method of reducing the effect of errors in the feedback of channel state information from a receiver to a transmitter, comprising
   choosing multiple mappings of indices to channel states,
   estimating the effect on transmission quality of feedback errors for each of the mappings of indices to channel states,
   selecting a mapping of indices to channel states to reduce the effect of feedback errors, and
   transmitting feedback of channel state information from the receiver to the transmitter, the receiver representing a channel state using the index determined by the selected mapping of indices to channel states.

2 The method of claim 1 in which error detection is used in the transmission of feedback.

3 The method of claim 1 in which error correction is used in the transmission of feedback.

4 The method of claim 1 in which channel prediction is used to detect errors.

5 The method of claims 2, 3 or 4 in which the transmitter discards feedback determined to be erroneous.

6 The method of claims 2, 3, or 4 in which the transmitter attempts to recover erroneous feedback.

7 The method of claim 1 in which a distance metric is used to estimate the effect on transmission quality of the transmitter erroneously using one channel state instead of another.
8. The method of claim 7 in which the chosen multiple mappings of indices to channel states include mappings chosen by a method comprising
   selecting pairs of channel states with a small distance between them,
   for each pair of channel states, selecting for the channel states indices that have a high probability of being mistaken for one another.

9. The method of claim 1 in which the chosen multiple mappings of indices to channel states include at least one mapping modified from another mapping by interchanging pairs of indices.

10. A method of assigning indices to channel states in order to reduce the impact of errors in the feedback of channel state information from a receiver to a transmitter, comprising
    selecting a pair of channel states that are close together according to a distance measure, and
    assigning indices to any channel states in the pair that have not already been assigned indices so as to minimize the Hamming distance between the indices.

11. A method of improving an assignment of indices to channel states in order to reduce the impact of errors in the feedback of channel state information from a receiver to a transmitter, comprising
    selecting a pair of channel states which already have indices assigned to them,
    determining if swapping the indices assigned to the states will reduce the impact of errors in the feedback of channel state information, and
    reassigning the indices according to the determination of the previous step.

12. A method of operating a multiple antenna communication system, the system comprising a transmitter and one or more receivers, comprising
    each receiver estimating its channel state,
    each receiver selecting an index representing a channel state based on its respective estimated channel state,
each receiver transmitting its respective selected index to the transmitter, and
the transmitter transmitting information to one or more of the receivers, using the
selected indices to estimate the channel state

13 The method of claim 12 further comprising
each receiver encoding its respective selected index using an error-detecting code,
each receiver transmitting transmitting its respective selected index to the transmitter
by transmitting its respective encoded index to the transmitter,
the transmitter decoding the encoded indices using an error-detecting decoder, and
the transmitter transmitting information to one or more of the receivers, using the
decoded indices as the selected indices to estimate the channel state

14 The method of claim 12 or 13 in which selecting an index is carried out by assigning
of indices to channel states according to the method of claim 1, 10 or 11, or the respective
methods of Figs 4, 5, 6, 7, 8 or 9

15 The method of claim 12, 13 or 14 in which the indices are encoded at the receivers
using an error correcting code, and decoded at the receiver using an error-correcting decoder

16 The method of any one of claims 12-15 in which the transmitter attempts to determine
if each received index is correct or erroneous

17 The method of any one of claims 12-16 in which the transmitter does not use indices
determined to be erroneous in transmitting to the receivers

18 The method of any one of claims 12-17 in which the transmitter attempts to recover
indices determined to be erroneous

19 The method of claim 18 in which the transmitter uses channel prediction to recover the
indices determined to be erroneous
An apparatus comprising
a receiver comprising one or more antennas and a receiver processing module,
a transmitter comprising antennas and a transmitter processing module, and
the receiver processing module and transmitter processing module being configured to
carry out the method steps of any one of claims 12-19
Fig. 3a  Good indexing

Fig. 3b  Poor indexing
Fig. 4

1. Initialize iteration counter $i \leftarrow 0$

2. Initialize previous best $GDP_{\text{previous}}$

3. Run Initialization phase (Fig. 5)

4. Run Optimization phase (Fig. 6)

5. Store index map and calculate the new global distance profile $GDP(e)$

6. Compare $GDP(e)$ with $GDP_{\text{previous}}$

7. Is the $GDP(e)$ better?
   - YES: Exchange $GDP_{\text{previous}}$ with $GDP(e)$. Store the current index map.
   - NO: Increase $i$ by 1

8. Is $i \sim P$?
   - YES: STOP
   - NO: Continue
Fig. 5

102. Distance matrix D is generated

104. The lists of unassigned indices, centroids and processed entries in D are initialized

106. Find the smallest unprocessed entry $d_{ki}$ in D and mark it as processed

108. Search for centroids $V_k$ and $V_i$ corresponding to $d_{ki}$

110. Any indices assigned to $V_k$ or $V_i$?

112. Yes: Assign centroid $V_k$ a random unassigned index $i$

114. NO: Index assigned to only one of $V_k$ or $V_i$?

116. Yes: Assume that the centroid with assigned index is mapped to the index $i$

118. NO: Assign the other centroid an unassigned index $j$ so that the Hamming distance $H_j$ is minimized

120. Mark the assigned indices and centroids as processed

122. Any unassigned indices left?

124. STOP
Fig. 6

130 Distance matrix $D$ is generated and the global distance profile $GDP(e)$ is initialized.

132 The list of processed entries in $D$ is initialized.

134 Set $GDP_{previous} = GDP(e)$.

136 Find the smallest unprocessed entry $d_{kl}$ in $D$ and mark it as processed.

138 Search for centroids $V_k$ and $V_l$ and their previously assigned indexes $i$ and $j$ corresponding to $d_{kl}$.

140 Calculate global distance profile with the original mapping $GDP_{original}(e)$.

142 Temporarily swap the mapping between centroids $V_k$ and $V_l$ and their indexes $i$ and $j$ so that $V_k$ is mapped to index $j$ and $V_l$ is mapped to index $i$.

144 Calculate global distance profile with the swapped mapping $GDP_{swapped}(e)$.

146 Does $GDP_{swapped}(e)$ better than $GDP_{original}(e)$?

148 YES Keep the swapped index mapping. Set $GDP(e)$

150 Any unprocessed entries in $D$ left?

152 YES GDP(e) improved GDP_{previous}?

154 STOP

154 NO GDP(e) improved GDP_{previous}?
Fig. 7

160 Initialize transmission epoch $t=1$

162 Each receiver estimates its channel matrix $H[i]$

164 Each receiver selects the best channel state information (CSI) index

166 The selected CSI index is encoded using an error-detecting code

168 **Optional.** The selected CSI index is further encoded using an error-correcting code

170 CSI indices are sent to the base station

172 **Optional.** The received CSI indices are decoded by error-correcting decoder

174 The received CSI indices are decoded by an error-detecting decoder

176 Were there errors?

178 **YES** Should erroneous indices be removed?

180 **YES** Expurgate erroneous indices

182 **Optional.** Attempt to recover the erroneous indices; or

184 If no error recovery is possible, mark erroneous indices as correct

186 Select the active users and schedule transmission

188 Increase $t$ by 1
Fig. 8

190 Initialize transmission epoch $t=1$

192 Each receiver estimates its channel matrix $H[i]$

194 Each receiver selects the best channel state information (CSI) index

196 Optional. The selected CSI index is further encoded using an error-correcting code

198 CSI indices are sent to the base station

200 Optional. The received CSI indices are decoded by error-correcting decoder

202 Can erroneous indices be detected?

YES

204 Optional. Attempt to recover the erroneous indices; or

Expurgate erroneous indices

NO

206 Use received indices as correct

208 Select the active users and schedule transmission

210 Increase $t$ by 1
Choose multiple mappings of indices to channel states

For each mapping, estimate the effect on transmission quality of feedback errors if the mapping is used to select indices to represent channel states

Select a mapping to reduce the effect of feedback errors

Send feedback of channel state information to the transmitter using the selected mapping of indices to channel states
INTERNATIONAL SEARCH REPORT

International application No
PCT/CA2009/000464

A CLASSIFICATION OF SUBJECT MATTER
IPC H04B 7/005 (2006 01) , H04W 16/00 (2009 01) , H04W 24/00 (2009 01)
According to International Patent Classification (IPC) or to both national classification and IPC

B FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
P C H04B, H04Q, H04W

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
google, Canadian Patent Database, WEST, IEEE

Keywords - map*, channel state, CSI, error, feedback, feedback, indices, index

C DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
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<td>A</td>
<td>CA2548919 (Kwon et al) 23 June 2005 (23-06-2005) ** see entire document **</td>
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<td>X, P</td>
<td>US20090067512A1 (Mielczarek et al) 12 March 2009 (12-03-2009) ** see entire document **</td>
<td>1-9</td>
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</table>

[ ] Further documents are listed in the continuation of Box C
[ ] See patent family annex

Date of the actual completion of the international search: 12 June 2009 (12-06-2009)
Date of mailing of the international search report: 30 July 2009 (30-07-2009)

Name and mailing address of the ISA/CA
Canadian Intellectual Property Office
Place du Portage I, Cl 14 - 1st Floor, Box PCT
50 Victoria Street
Gatineau, Quebec K1A 0C9
Facsimile No 001-819-953-2476

Authorized officer
Leah Smith 819-956-9966

Form PCT/ISA/210 (second sheet) (July 2008)
**INTERNATIONAL SEARCH REPORT**

<table>
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<th>Box No. II</th>
<th>Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)</th>
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<td>This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons</td>
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<td>1 [ ]</td>
<td>Claim Nos because they relate to subject matter not required to be searched by this Authority, namely</td>
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<tr>
<td>2 [ ]</td>
<td>Claim Nos because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically</td>
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<td>3 [ ]</td>
<td>Claim Nos because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)</td>
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<th>Observations where unity of invention is lacking (Continuation of item 3 of first sheet)</th>
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<td>This International Searching Authority found multiple inventions in this international application, as follows</td>
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<td></td>
<td>Group A - 1 to 9, Group B - 10, Group C - 11, and Group D - 12-20</td>
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<tr>
<td>1 [ ]</td>
<td>As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims</td>
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<td>As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees</td>
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<td>As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos</td>
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<td>4 [X]</td>
<td>No required additional search fees were timely paid by the applicant Consequently, this international search report is restricted to the invention first mentioned in the claims, it is covered by claim Nos 1-9</td>
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**Remark on Protest**

[ ] The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee

[ ] The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation

[ ] No protest accompanied the payment of additional search fees
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<td>CA 25489 19A1</td>
<td>23-06-2005</td>
<td>AT 408321 T</td>
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<td>WO 2005057812 A1</td>
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The application contains four groups of inventions as follows:

Group A - Claims 1-9 are directed to a method of reducing the effect of errors in the feedback channel wherein mappings of indices to channel states are selected to reduce the effect of feedback errors.

Group B - Claim 10 is directed to a method of assigning indices to channel states in order to reduce the impact of feedback errors comprising assigning indices to any channel states in a pair of channel states not already assigned indices in order to minimize the Hamming distance between the indices.

Group C - Claim 11 is directed to a method of improving an assignment to indices to channel states in order to reduce the impact of feedback error comprising reassigning indices according to whether swapping the indices assigned to states in a pair of channel states will reduce the impact of feedback errors.

Group D - Claims 12-20 are directed to a method of operating a multiple antenna communication system comprising assigning an index to a channel state based on an estimation of the channel state and transmitting the index to the transmitter who transmits information back to the receiver using the selected indices.