

METHOD AND APPARATUS FOR MAXIMUM LIKELIHOOD DETECTION IN MIMO RECEIVER

Technical Field

5 The invention relates to a digital receiver design for a Multiple Input Multiple Output (MIMO) system, and particularly to maximum likelihood detection (MLD) equalization method and apparatus thereof.

Background

10 To improve signal reception and recovery in wireless networks operating in unfavourable conditions such as interference, reflections, etc., Multiple Input Multiple Output (MIMO) channels have been employed; maximum likelihood detector (MLD) have been employed to determine at the receiver the probabilities of the transmitted signal and select the likely transmitted signal.

15 In the following paper: Y. Lomnitz and D. Andelman, "Efficient maximum likelihood detector for MIMO systems with small number of streams", *Electronics Letters*, 25th October 2007, Vol. 43, No. 22., the authors devised a method to calculate maximum likelihood ratio (LLR) for a 2x2 MIMO equalizer by using linear complexity. The resulting LLR is equivalent to the LLR calculated using conventional
20 brute force O^2 complexity.

 Given the 2x2 channel matrix H , 2x1 received signal vector y , and noise power σ^2 , the distance is calculated as $D=|y-Hc|^2/\sigma^2$, wherein c is a 2x1 vector of the QAM constellation points. The conventional brute force method requires all D of all possible candidates of c to be computed. For example, for a 2x2 MIMO 64QAM
25 signal, there are a total of 64x64 combinations of c . The candidate of c which corresponds to the smallest D is the candidate that is to be chosen to calculate the hard decision and soft decision (LLR) of the maximum likelihood decoder.

 The aforementioned paper drastically reduces the number of candidates by first using maximum ratio combining (MRC) to solve for the successful candidate of
30 one stream, and then using this successful candidate to do a linear search for the minimum distance.

Particularly, the aforementioned paper discloses the following steps:

(1) Define y_1 and y_2 as the components of signal vector y

(2) Define $\{h_{11}, h_{12}\}$ as the first row of channel gain H matrix, and $\{h_{21}, h_{22}\}$ as the second row

5 (3) Define c_1 and c_2 as the components of constellation point vector c

(4) Define $c_{1\text{mrc}}$ and $c_{2\text{mrc}}$ as the MRC solution for each stream

(5) Calculate distance as

$$\text{For stream 1, } D = |y_1 - h_{11} * c_1 - h_{12} * c_{2\text{mrc}}|^2 + |y_2 - h_{21} * c_1 - h_{22} * c_{2\text{mrc}}|^2$$

$$\text{For stream 2, } D = |y_1 - h_{11} * c_{1\text{mrc}} - h_{12} * c_2|^2 + |y_2 - h_{21} * c_{1\text{mrc}} - h_{22} * c_2|^2$$

10 wherein $c_{1\text{mrc}}$ is calculated by choosing the constellation closest to the MRC solution

$$((\text{conj}(h_{11}) * y_1 - h_{12} * c_2) + (\text{conj}(h_{21}) * y_2 - h_{22} * c_2)) / (\text{conj}(h_{11}) * h_{11} + \text{conj}(h_{12}) * h_{12})$$

wherein $c_{2\text{mrc}}$ is calculated by choosing the constellation closest to the MRC solution

$$((\text{conj}(h_{12}) * y_1 - h_{11} * c_1) + (\text{conj}(h_{22}) * y_2 - h_{21} * c_1)) / (\text{conj}(h_{12}) * h_{12} + \text{conj}(h_{22}) * h_{22})$$

The aforementioned process of choosing the closest constellation is known as

15 slicing.

Although the above the aforementioned paper has significantly reduced the number of searches for calculating minimum distance, it still separately searches two streams for the minimum distance. Accordingly, method and apparatus for further reducing the number of searches are highly desirable.

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Summary

According to a first aspect of the invention, an equalization method for maximum likelihood detection in a wireless MIMO channel having a transmitted
25 signal vector x and a received signal vector y is provided. The method comprises:

obtaining a channel gain matrix H and a noise variance σ^2 ;

obtaining an upper triangular matrix R and a constant beta value β by applying Cholesky decomposition to a product of the channel gain matrix H and a conjugate transpose of the channel gain matrix H' ;

30 obtaining the received signal vector y which comprises received signals from the MIMO channel;

applying a modified channel gain matrix $(H'H)^{-1}H'$ to the received signal vector y to produce a zero-forcing solution vector s which at least comprises a

first zero-forcing solution s_1 and a second zero-forcing solution s_2 , wherein modified channel gain matrix $(H'H)^{-1}H'$ is calculated from a product of an inverse of a product of a conjugate transpose of the channel gain matrix H' and the channel gain matrix H , and a conjugate transpose of the channel gain matrix H' ;

for a second QAM constellation point vector c_2 having a n number of constellation points therein, obtaining a n number of soft estimates $c_{1\text{soft}}$ based at least on the upper triangular matrix R , the first zero-forcing solution s_1 and the second QAM constellation point vector c_2 ;

slicing the n number of soft estimates $c_{1\text{soft}}$ to produce a n number of hard decision results $c_{1\text{chol}}$ corresponding to the second QAM constellation point vector c_2 ; and

calculating a plurality of distance metrics D , which comprises:

for each constellation point from at least some of the n number of constellation points comprised in the second QAM constellation point vector c_2 , calculating a distance metric based at least on

the upper triangular matrix R ,

the second zero-forcing solution s_2 ,

the each constellation point comprised in the second QAM

constellation point vector s_2 ,

a corresponding hard decision result from the n number of hard decision result $c_{1\text{chol}}$, and

the noise variance σ^2 .

With reference to the first aspect, in a first possible implementation manner of the first aspect, the method further comprises:

identifying a minimum distance metric $D_{\min}$ from the plurality of distance metrics D ;

using the identified minimum distance metric $D_{\min}$, identifying a corresponding QAM constellation point from the second QAM constellation point vector c_2 as an estimated transmitted signal x_2 .

With reference to the first aspect or the first possible implementation manner of the first aspect, in a second possible implementation manner of the first aspect, the at least some of the n number of constellation points include a first constellation point corresponding to the second zero-forcing solution s_2 and a plurality of second constellation points which are closest to the first constellation point.

With reference to any of the first aspect, the first to second possible implementation manner of the first aspect, in a third possible implementation manner of the first aspect, the step of obtaining a n number of soft estimates $c_{1\text{soft}}$ based at least on the upper triangular matrix R, a first zero-forcing solution s_1 and the second QAM constellation point vector c_2 comprises:

calculating $\text{slicer}\{c_1\} = \text{slicer}\{(r_{11}s_1 + r_{12}(s_2 - c_2)/r_{11})\}$ wherein r_{11} and r_{12} are comprised in the upper triangular matrix R;

wherein calculating a n number of distance metrics D comprises:

$$D = \frac{(|r_{22}(s_2 - c_2)|^2 + |r_{11}(s_1 - \text{slicer}\{c_1\}) + r_{12}(s_2 - c_2)|^2)}{\text{beta} \times \sigma^2}$$

With reference to any of the first aspect, the first to third possible implementation manner of the first aspect, in a fourth implementation manner of the first aspect, the MIMO channel is $M \times N$ channel wherein $M=2$ and $N=2$.

According to a second aspect of the invention, an equalizer for implementing maximum likelihood detection in a wireless MIMO channel having a transmitted signal vector x and a received signal vector y is provided. The equalizer comprises:

a Cholesky decomposition module configured to:

obtain a channel gain matrix H and a noise variance σ^2 ;

obtain an upper triangular matrix R and a constant beta value β by applying Cholesky decomposition to a product of the channel gain matrix H and a conjugate transpose of the channel gain matrix H^H ;

obtain the received signal vector y which comprises received signals from the MIMO channel;

a zero-forcing module configured to:

apply a modified channel gain matrix $(H'H)^{-1}H'$ to the received signal vector y to produce a zero-forcing solution vector s which at least comprises a first zero-forcing solution s_1 and a second zero-forcing solution s_2 , wherein modified channel gain matrix $(H'H)^{-1}H'$ is calculated from a product of an inverse of a product of a conjugate transpose of the channel gain matrix H' and the channel gain matrix H , and a conjugate transpose of the channel gain matrix H' ; a distance calculation and signal estimation module configured to:

for a second QAM constellation point vector c_2 having a n number of constellation points therein, obtain a n number of soft estimates $c_{1\text{soft}}$ based at least on the upper triangular matrix R , the first zero-forcing solution s_1 and the second QAM constellation point vector c_2 ;

slice the n number of soft estimates $c_{1\text{soft}}$ to produce a n number of hard decision results $c_{1\text{chol}}$ corresponding to the second QAM constellation point vector c_2 ; and

calculate a plurality of distance metrics D , which comprises:

for each constellation point from at least some of the n number of constellation points comprised in the second QAM constellation point vector c_2 , calculate a distance metric based at least on the upper triangular matrix R , the second zero-forcing solution s_2 , the each constellation point comprised in the second QAM constellation point vector s_2 , a corresponding hard decision result from the n number of hard decision result $c_{1\text{chol}}$, and the noise variance σ^2 .

According to a third aspect of the invention, an equalizer for implementing maximum likelihood detection in a wireless MIMO channel having a transmitted signal vector x and a received signal vector y is provided. The equalizer comprises:

a processor and a storage medium communicably coupled thereto, wherein the storage medium is configured to store instructions to be executed by the processor, wherein the processor is configured to: perform the steps described in relation to the first aspect of the invention.

Detailed Description of the Invention

In the following description, numerous specific details are set forth in order to provide a thorough understanding of various illustrative embodiments of the invention. It will be understood, however, to one skilled in the art, that embodiments of the invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure pertinent aspects of embodiments being described. In the drawings, like reference numerals refer to same or similar functionalities or features throughout the several views.

One embodiment of the invention is described with reference to a MIMO system having M number of transmit antennas, N number receive antennas. This embodiment will be illustrated by a 2x2 MIMO system where M=2, N=2. It is assumed that a 2x2 channel gain matrix, H, has been ascertained using known techniques, and provided to an equalizer in the MIMO system. It is assumed that the equalizer will receive a 2x1 complex received signal vector, y, comprising {y₁; y₂}, at the two receive antennas wherein y results from a 2x1 complex transmitted signal vector x, comprising {x₁; x₂}, sent by the two transmit antennas. The transmitted signal vector x is modulated using Quadrature amplitude modulation (QAM) and results in constellation with the number of points equal to 16, i.e. 16 QAM, 64, i.e. 64 QAM, 128, i.e. 128 QAM, etc.

Distance D for each possible combination of x is calculated by Equation 1:

$$D = \frac{|y-Hc|^2}{\sigma^2} \quad (\text{Equation 1})$$

wherein c is a complex vector of the candidate QAM point of the constellation (i.e. {±1, ±3, ±5, ±7,...}/QAM_normalizer, where QAM_normalizer is the scaling such that the QAM constellation average power is 1.0, and σ² is the noise variance.

The candidate vector c, which corresponds to the minimum distance D_{min} among all the possible distances would be the successful candidate in determining the likely transmitted signal, wherein n is the number of constellation points.

Equation 1 can be rewritten as:

$$D = \frac{|H(H^{-1}y-c)|^2}{\sigma^2} = \frac{|H(s-c)|^2}{\sigma^2} \quad (\text{Equation 2})$$

wherein $s=(H'H)^{-1}H'y$, which is a solution to zero-forcing.

Given that channel gain matrix $H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$, the inverse matrix of $(H'H)^{-1}$ is calculated by

$$\begin{bmatrix} |h_{11}|^2 + |h_{22}|^2 & -(h_{11}'h_{12} + h_{21}'h_{22}) \\ -(h_{11}h_{12}' + h_{21}h_{22}') & |h_{11}|^2 + |h_{21}|^2 \end{bmatrix} / |h_{11}h_{22} - h_{21}h_{12}|^2$$

5 By multiplying D of Equation 2 with a unitary matrix, (i.e. such that the value D does not change), Equation 2 can be rearranged as

$$D = \frac{|R(s-c)|^2}{\text{beta} \times \sigma^2} \quad (\text{Equation 3})$$

wherein R is obtained from Cholesky decomposition $R'R/\text{beta}=\text{chol}(H'H)$, wherein R' is conjugate transpose of R, and wherein H' is conjugate transpose of H. The
10 Cholesky decomposition of $H'H$ is calculated by

$$\text{chol}(H'H)=R'R/\text{beta}$$

wherein $R = \begin{bmatrix} |h_{11}|^2 + |h_{21}|^2 & h_{11}'h_{12} + h_{21}'h_{21} \\ 0 & |h_{11}h_{22} - h_{12}h_{21}| \end{bmatrix}$ and $\text{beta} = 1/(|h_{11}|^2 + |h_{21}|^2)$ which is a constant value.

By defining R as an upper right triangular matrix, $R = \begin{bmatrix} r_{11} & r_{12} \\ 0 & r_{22} \end{bmatrix}$, $s = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}$,

15 and $c = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix}$, Equation 3 can be expanded into

$$D = \frac{(|r_{22}(s_2 - c_2)|^2 + |r_{11}(s_1 - c_1) + r_{12}(s_2 - c_2)|^2)}{\text{beta} \times \sigma^2} \quad (\text{Equation 4})$$

By solving for a partial equation from D, i.e. by solving $|r_{11}(s_1 - c_1) + r_{12}(s_2 - c_2)|^2 = 0$, such that c_1 is eliminated from Equation 4, the following is obtained:

$$\text{slicer}\{c_1\} = \text{hard}\{(r_{11}s_1 + r_{12}(s_2 - c_2)/r_{11})\} \quad (\text{Equation 5})$$

20 wherein $\text{hard}\{\}$ denotes locating the closest point in the constellation $\{\pm 1, \pm 3, \pm 5, \pm 7, \dots\}/\text{QAM_normalizer}$, where QAM_normalizer is the scaling such that the QAM constellation average power is 1.0.

Accordingly, Equation 4 can be rewritten as

$$D = \frac{(|r_{22}(s_2 - c_2)|^2 + |r_{11}(s_1 - \text{ slicer}\{c_1\}) + r_{12}(s_2 - c_2)|^2)}{\text{beta} \times \sigma^2} \quad (\text{Equation 6})$$

$$\text{Soft estimate } c_{1\text{soft}} = (r_{11}s_1 + r_{12}(s_2 - c_2)/r_{11}) \quad (\text{Equation 7})$$

wherein $c_{1\text{soft}}$ comprises n number of soft estimate constellation point values, and
 5 wherein n is number of constellation points.

$$\text{Hard decision result } c_{1\text{chol}} = \text{ slicer } \{(r_{11}s_1 + r_{12}(s_2 - c_2)/r_{11})\} = \text{ slicer}\{c_{1\text{chol}}\} \quad (\text{Equation 8})$$

Equations 6 to 8 are to be applied in an equalization method for maximum likelihood detection for a wireless MIMO channel having a transmitted signal vector x
 10 and a received signal vector y. Particularly, Equations 7 and 8 are first computed and the results therefrom are supplied to compute Equation 6. An equalization method is described with reference to flow sequence 100 in Figure 1.

In block 102, a channel gain matrix H and a noise variance σ^2 are obtained or calculated based on channel characteristics.

15 In block 104, an upper triangular matrix R and a beta value β , which is a constant value, are obtained by applying Cholesky decomposition to a product of the channel gain matrix H and a conjugate transpose of the channel gain matrix H';

In block 106, a received signal vector y is obtained, which comprises received signals from the MIMO channel.

20 In block 108, a modified channel gain matrix $(H'H)^{-1}H'$ is applied to the received signal vector y to produce a zero-forcing solution vector s which at least comprises a first zero-forcing solution s_1 and a second zero-forcing solution s_2 . The modified channel gain matrix $(H'H)^{-1}H'$ is calculated from a product of an inverse of a product of a conjugate transpose of the channel gain matrix H' and the channel gain matrix H, and a conjugate transpose of the channel gain matrix H'.

25 In block 110, for the second QAM constellation point vector c_2 , a n number of soft estimates $c_{1\text{soft}}$ is obtained based at least on the upper triangular matrix R, the first zero-forcing solution s_1 and the second QAM constellation point vector c_2 . The n number of soft estimates $c_{1\text{soft}}$ are calculated by Equation 7.

In block 112, the n number of soft estimates $c_{1\text{soft}}$ is sliced to produce a n number of hard decision results $c_{1\text{chol}}$ corresponding to the second QAM constellation point vector c_2 . The n number of hard decision results $c_{1\text{chol}}$ are calculated by Equation 8. After this slicing step, a unique hard decision result, i.e. slicer $\{c_1\}$, is obtained for each constellation point of the second QAM constellation point vector c_2 , without compromising the search for the minimum distance metrics.

In block 114, a plurality of distance metrics D are ascertained or calculated by the following step(s): for each constellation point comprised in the second QAM constellation point vector c_2 , calculating a distance metric based at least on: the upper triangular matrix R , the second zero-forcing solution s_2 , the each constellation point comprised in the second QAM constellation point vector s_2 , a corresponding hard decision result from the n number of hard decision result $c_{1\text{chol}}$, and the noise variance σ^2 . The distance metrics D are calculated by Equation 6.

From Equation 6, each combination of c_2 has a unique corresponding c_1 . Therefore the total number of D is equal to the number of constellation points, e.g. 64 for 64QAM.

In block 116, a minimum distance metric $D_{\min}$ is identified from the plurality of distance metrics D is identified.

In block 118, using the identified minimum distance metric from block 116, a corresponding QAM constellation point from the second QAM constellation point vector c_2 as an estimated transmitted signal x_2 is identified.

It is to be appreciated that some of the above sequence may be interchanged or modified, for example, block 106 may take place prior to blocks 102 and 104.

It is to be appreciated that the identified minimum metrics $D_{\min}$ (from block 116) may be applied in two ways: either as hard decision solution to x , or as soft decision solution to x . Hard decision solution to x is the corresponding $[c_1 \ c_2]$ to $D_{\min}$. Soft decision solution to x is computed from $D_{\min}$ from known techniques in the art.

It is to be appreciated that a smaller set of distance metrics may be ascertained or calculated in block 114 to reduce complexity. To this purpose, using the result of zero-forcing from block 108, i.e. second zero-forcing solution s_2 , a first constellation point corresponding to the second zero-forcing solution s_2 and a

plurality of second constellation points which are closest to the first constellation point are identified or selected. Thereafter, distance metrics corresponding to the first and the plurality of second constellation points are calculated, and a minimum distance $D_{\min}$ is selected from this smaller set of distance metrics. In this smaller set of distance metrics, the number of calculated distance metrics is smaller than the number of constellation points. For example, in 64QAM, if the first constellation point is ascertained as $\{I, Q\} = \{+5, +3\}$, the plurality of second constellation points, e.g. four points, which are closest to the first constellation point would be selected for calculating their corresponding distance metrics so that the minimum distance metric is selected therefrom, e.g. select minimum one of the four corresponding distance metrics.

According to one embodiment of the invention, an equalizer comprises: a processor and a storage medium communicably coupled thereto, wherein the storage medium is configured to store instructions to be executed by the processor, wherein the processor is configured to execute the aforementioned sequence 100 or a modified sequence thereof.

According to one embodiment of the invention, an equalizer 200 has a schematic representation illustrated by Figure 2. The equalizer 200 is configured to receive the channel matrix gain H and received signal vector y , and produce at the output an estimated transmitted signal x_2 . The equalizer 200 comprises: a Cholesky decomposition module 202, a zero-forcing module 204 and a distance calculation and estimation module 206. The Cholesky decomposition module is configured to perform the sequence described in blocks 102, 104, 106. The zero-forcing module 204 is configured to perform the sequence described in block 108. The distance calculation and estimation module 206 is configured to perform the sequence described in blocks 110 to 114.

Embodiments of the invention are advantageous for at least the following reasons:

In the aforementioned paper by Y. Lomnitz and D. Andelman, the number of searches required to locate minimum distance $D_{\min}$ is equivalent to the total number of candidates of c_1 and c_2 . For example, with constellation size of 64, the number of searches required for a 2x2 MIMO equalizer is 128; the number of operations for one

set of distance calculation using MRC-MLD, of the aforementioned paper, involves 8 multipliers, 10 adders, 4 squares; the number of operations for one set of reduced candidate using MRC-MLD, of the aforementioned paper, involves 8 multipliers, 6 adders.

5 In contrast, with the invention, the number of searches required to locate minimum distance $D_{\min}$ is equivalent to the number of candidates of c_2 . For example, with constellation size of 64, the number of searches required for a 2x2 MIMO equalizer is 64; the number of operations for one set of distance calculation using Cholesky-MLD involves 3 multipliers, 5 adders, 2 squares; the number of operations
10 for one set of reduced candidate using Cholesky-MLD involves 2 multipliers, 2 adders.

In view of the above, the invention achieves 50% reduction in number of searches as compared to the aforementioned paper. Further, in implementing MLD, most of the hardware are concentrated on the slicer{.} function and the minimum
15 distance search function. Therefore, reducing the number of candidates to be searched greatly contributes to the reduction of required hardware size.

The invention can be applied to MIMO configuration higher than 2x2 to achieve reduced number of searches. However, the invention's MLD solution for any configuration higher than 2x2 would not be equivalent to the conventional brute force
20 method. Also, for any configuration (2x2 or higher), the number of searches can be reduced by using a subset of c_2 candidates. Further, zero-forcing and Cholesky decomposition results can be used for other WIFI receiver purposes not related to MLD, for example, TxBF, equalizer power reduction, channel condition estimate.

25 Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the invention. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the disclosed embodiments of the invention. The embodiments and features described above should be considered exemplary.

Claims

1. An equalization method for maximum likelihood detection in a wireless MIMO channel having a transmitted signal vector x and a received signal vector y , the

5 method comprising:

obtaining a channel gain matrix H and a noise variance σ^2 ;

obtaining an upper triangular matrix R and a constant beta value β by applying Cholesky decomposition to a product of the channel gain matrix H and a conjugate transpose of the channel gain matrix H' ;

10 obtaining the received signal vector y which comprises received signals from the MIMO channel;

applying a modified channel gain matrix $(H'H)^{-1}H'$ to the received signal vector y to produce a zero-forcing solution vector s which at least comprises a first zero-forcing solution s_1 and a second zero-forcing solution s_2 , wherein modified channel gain matrix $(H'H)^{-1}H'$ is calculated from a product of an inverse of a product of a conjugate transpose of the channel gain matrix H' and the channel gain matrix H , and a conjugate transpose of the channel gain matrix H' ;

for a second QAM constellation point vector c_2 having a n number of constellation points therein, obtaining a n number of soft estimates $c_{1\text{soft}}$ based at least on the upper triangular matrix R , the first zero-forcing solution s_1 and the second QAM constellation point vector c_2 ;

slicing the n number of soft estimates $c_{1\text{soft}}$ to produce a n number of hard decision results $c_{1\text{chol}}$ corresponding to the second QAM constellation point vector c_2 ; and

25 calculating a plurality of distance metrics D , which comprises:

for each constellation point from at least some of the n number of constellation points comprised in the second QAM constellation point vector c_2 , calculating a distance metric based at least on the upper triangular matrix R , the second zero-forcing solution s_2 , the each constellation point comprised in the second QAM constellation point vector s_2 , a corresponding hard decision result from the n number of hard decision result $c_{1\text{chol}}$, and the noise variance σ^2 .

2. The method of claim 1, further comprising:

identifying a minimum distance metric $D_{\min}$ from the plurality of distance metrics D ;

using the identified minimum distance metric $D_{\min}$, identifying a corresponding

5 QAM constellation point from the second QAM constellation point vector c_2 as an estimated transmitted signal x_2 .

3. The method of claim 1 or 2, wherein the at least some of the n number of constellation points include a first constellation point corresponding to the second zero-forcing solution s_2 and a plurality of second constellation points which are
10 closest to the first constellation point.

4. The method of any of claims 1 to 3, wherein obtaining a n number of soft estimates $c_{1\text{soft}}$ based at least on the upper triangular matrix R , a first zero-forcing solution s_1 and the second QAM constellation point vector c_2 comprises:
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calculating $\text{slicer}\{c_1\} = \text{slicer}\{(r_{11}s_1 + r_{12}(s_2 - c_2)/r_{11})\}$ wherein r_{11} and r_{12} are comprised in the upper triangular matrix R ;

wherein calculating a n number of distance metrics D comprises:

$$\text{calculating } D = \frac{(|r_{22}(s_2 - c_2)|^2 + |r_{11}(s_1 - \text{slicer}\{c_1\}) + r_{12}(s_2 - c_2)|^2)}{\text{beta} \times \sigma^2}$$

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5. The method of any of claims 1 to 4, wherein the MIMO channel is $M \times N$ channel wherein $M=2$ and $N=2$.

6. An equalizer for implementing maximum likelihood detection in a wireless MIMO
25 channel having a transmitted signal vector x and a received signal vector y , the equalizer comprising:

a Cholesky decomposition module configured to:

obtain a channel gain matrix H and a noise variance σ^2 ;

obtain an upper triangular matrix R and a constant beta value β by

30 applying Cholesky decomposition to a product of the channel gain matrix H and a conjugate transpose of the channel gain matrix H' ;

obtain the received signal vector y which comprises received signals from the MIMO channel;

a zero-forcing module configured to:

5 apply a modified channel gain matrix $(H'H)^{-1}H'$ to the received signal vector y to produce a zero-forcing solution vector s which at least comprises a first zero-forcing solution s_1 and a second zero-forcing solution s_2 , wherein modified channel gain matrix $(H'H)^{-1}H'$ is calculated from a product of an inverse of a product of a conjugate transpose of the channel gain matrix H' and the channel gain matrix H , and a conjugate transpose of the channel gain matrix H' ;

a distance calculation and signal estimation module configured to:

15 for a second QAM constellation point vector c_2 having a n number of constellation points therein, obtain a n number of soft estimates $c_{1\text{soft}}$ based at least on the upper triangular matrix R , the first zero-forcing solution s_1 and the second QAM constellation point vector c_2 ;

 slice the n number of soft estimates $c_{1\text{soft}}$ to produce a n number of hard decision results $c_{1\text{chol}}$ corresponding to the second QAM constellation point vector c_2 ; and

20 calculate a plurality of distance metrics D , which comprises:

 for each constellation point from at least some of the n number of constellation points comprised in the second QAM constellation point vector c_2 , calculate a distance metric based at least on the upper triangular matrix R , the second zero-forcing solution s_2 , the each constellation point comprised in the second QAM constellation point vector s_2 , a corresponding hard decision result from the n number of hard decision result $c_{1\text{chol}}$, and the noise variance σ^2 .

7. The equalizer of claim 6, wherein the distance calculation and signal estimation module is further configured to:

30 identify a minimum distance metric $D_{\min}$ from the plurality of distance metrics D ;

using the identified minimum distance metric $D_{\min}$, identify a corresponding QAM constellation point from the second QAM constellation point vector c_2 as an estimated transmitted signal x_2 .

8. The equalizer of claim 6 or 7, wherein the at least some of the n number of constellation points include a first constellation point corresponding to the second zero-forcing solution s_2 and a plurality of second constellation points which are closest to the first constellation point.

9. The equalizer of any of claims 6 to 8, wherein the distance calculation and signal estimation module is further configured to:

calculate $\text{ slicer}\{c_1\} = \text{ slicer} \{ (r_{11}s_1 + r_{12}(s_2 - c_2)/r_{11}) \}$ wherein r_{11} and r_{12} are comprised in the upper triangular matrix R ;

wherein calculating a n number of distance metrics D comprises:

$$D = \frac{(|r_{22}(s_2 - c_2)|^2 + |r_{11}(s_1 - \text{ slicer}\{c_1\}) + r_{12}(s_2 - c_2)|^2)}{\text{beta} \times \sigma^2}$$

10. The equalizer of any of claims 6 to 9, wherein the MIMO channel is $M \times N$ channel wherein $M=2$ and $N=2$.

11. An equalizer for implementing maximum likelihood detection in a wireless MIMO channel having a transmitted signal vector x and a received signal vector y , the equalizer comprising:

a processor and a storage medium communicably coupled thereto, wherein the storage medium is configured to store instructions to be executed by the processor, wherein the processor is configured to:

obtain a channel gain matrix H and a noise variance σ^2 ;

obtain an upper triangular matrix R and a constant beta value β by applying Cholesky decomposition to a product of the channel gain matrix H and a conjugate transpose of the channel gain matrix H' ;

obtain the received signal vector y which comprises received signals from the MIMO channel;

apply a modified channel gain matrix $(H'H)^{-1}H'$ to the received signal vector y to produce a zero-forcing solution vector s which at least comprises a first zero-forcing solution s_1 and a second zero-forcing solution s_2 , wherein modified channel gain matrix $(H'H)^{-1}H'$ is calculated from a product of an inverse of a product of a conjugate transpose of the channel gain matrix H' and the channel gain matrix H , and a conjugate transpose of the channel gain matrix H' ;

for a second QAM constellation point vector c_2 having a n number of constellation points therein, obtain a n number of soft estimates $c_{1\text{soft}}$ based at least on the upper triangular matrix R , the first zero-forcing solution s_1 and the second QAM constellation point vector c_2 ;

slice the n number of soft estimates $c_{1\text{soft}}$ to produce a n number of hard decision results $c_{1\text{chol}}$ corresponding to the second QAM constellation point vector c_2 ; and

calculate a plurality of distance metrics D , which comprises:

for each constellation point from at least some of the n number of constellation points comprised in the second QAM constellation point vector c_2 , calculate a distance metric based at least on the upper triangular matrix R , the second zero-forcing solution s_2 , the each constellation point comprised in the second QAM constellation point vector s_2 , a corresponding hard decision result from the n number of hard decision result $c_{1\text{chol}}$, and the noise variance σ^2 .

12. The equalizer of claim 11, wherein the processor is further configured to:

identify a minimum distance metric D_{min} from the plurality of distance metrics D ;

using the identified minimum distance metric D_{min} , identify a corresponding QAM constellation point from the second QAM constellation point vector c_2 as an estimated transmitted signal x_2 .

13. The equalizer of claim 11 or 12, wherein the at least some of the n number of constellation points include a first constellation point corresponding to the second

zero-forcing solution s_2 and a plurality of second constellation points which are closest to the first constellation point.

14. The equalizer of any of claims 11 to 13, wherein the processor is further configured to:

calculate $\text{ slicer}\{c_1\} = \text{ slicer} \{ (r_{11}s_1 + r_{12}(s_2 - c_2))/r_{11} \}$ wherein r_{11} and r_{12} are comprised in the upper triangular matrix R;

wherein calculating a n number of distance metrics D comprises:

$$\text{calculate } D = \frac{(|r_{22}(s_2 - c_2)|^2 + |r_{11}(s_1 - \text{ slicer}\{c_1\}) + r_{12}(s_2 - c_2)|^2)}{\text{beta} \times \sigma^2}$$

15. The equalizer of any of claims 11 to 14, wherein the MIMO channel is $M \times N$ channel wherein $M=2$ and $N=2$.