A METHOD AND APPARATUS FOR COMPRESSED UPLINK DATA TRANSMISSION

FIELD OF THE INVENTION

This disclosure relates to compressing feedback of beamformer precoders for uplink data transmissions.

BACKGROUND

Advanced IEEE 802.11 Standards, such as 802.11ax, also referred to Wi-Fi 6, and 802.11be, also referred to Wi-Fi 7, support a very high data rate from 4.8Gbps up to 23Gbps. This is partially achieved by means of precoding the transmitted data streams such that the signal to noise ratio (SNR) is improved and a higher rate Modulation and Coding Scheme (MCS) can be used. Precoding has been used since 802.11n, for both downlink (DL) and uplink (UL); however, although Trigger Based (TB) transmissions have been used since 802.11ax, precoding is not supported for TB transmissions. Precoding for TB Physical layer Protocol Data Units (PPDUs) has been proposed for 802.11be and 802.11bn (also known as Ultra High Reliability – UHR and also referred to Wi-Fi 8). This is relevant for both Single User - Multiple Input Multiple Output (SU-MIMO) as well as Multiple User (MU) - MIMO. Unlike traditional 802.11 precoding, here the Access Point (AP) triggers the Station Devices (STAs) to transmit the (UL) Null Data Packet (NDP), based on which the AP computes the precoder(s) for each station device. The Access Point then needs to deliver the precoder to the Station Devices for use and trigger a precoded UL TB PPDU, which can be in the SU-MIMO or MU-MIMO mode.

Currently, precoding for UL TB PPDUs is not part of an IEEE 802.11 Standard. Therefore, there is no agreed way to structure or format the procedure. It is therefore desirable to develop an efficient and practical method for executing such a procedure and specify the necessary requirements of the devices involved for carrying out the method. In particular, this is true for compressing, quantizing and providing the precoder information to the intended transmitter.

SUMMARY OF THE INVENTION

According to one aspect there is provided a method for providing compressed and quantized precoder data to one or more station devices as part of a trigger-based uplink data communication of a wireless network, the method comprising: calculating at an access point of the wireless network a precoding matrix for each of the one or more station devices; decomposing the precoding matrix of each station device into a plurality of submatrices and forming compressed precoder data from a selection of the plurality of submatrices; and transmitting the compressed precoder data to each of the one or more station devices. The method may comprise, prior to calculating precoding matrices, triggering by the access point each of the one or more station devices to transmit a sounding null data packet to the access point.

In an embodiment, the precoder matrix may be decomposed using singular value decomposition, SVD, into submatrices where the submatrices comprise an orthonormal matrix, $\widetilde{\boldsymbol{U}}$, a diagonal matrix with real positive values, $\tilde{\boldsymbol{S}}$, and a unitary matrix $\widetilde{\boldsymbol{V}}^{H}$ according to the equation:

$$\boldsymbol{W} = \widetilde{\boldsymbol{U}}_{N_r \times N_c} \tilde{\boldsymbol{S}}_{N_c \times N_c} \widetilde{\boldsymbol{V}}^{H}_{N_c \times N_c} .$$

In an embodiment, the compressed precoder data may comprise an orthonormal submatrix **U** where the last row contains only real and positive numbers, and diagonal elements of a complex submatrix **S**.

In an embodiment, the compressed precoder data may comprise an orthonormal submatrix **U** where the last row contains only real and positive values, the diagonal elements of the submatrix $\tilde{\boldsymbol{S}}$ and a set of angles derived from the last row of **U**.

In an embodiment, the submatrix **U** may be computed according to the equation: $\boldsymbol{U} = \tilde{\boldsymbol{U}}\boldsymbol{\Theta}^{H}$ where $\tilde{\boldsymbol{U}}$ is an orthonormal matrix, $\boldsymbol{\Theta}^{H}$ is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\tilde{\boldsymbol{U}}$, and the matrix $\boldsymbol{U}$ is an orthonormal matrix with real and positive elements in the last row.

In an embodiment, the submatrix **S** may be computed according to the equation: $S = \boldsymbol{\Theta}\tilde{\boldsymbol{S}}$, where **S** is a diagonal complex matrix, $\tilde{\boldsymbol{S}}$ is a diagonal real and positive matrix, and **Θ** is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\tilde{\boldsymbol{U}}$.

In an embodiment, the compressed precoder data may comprise an orthonormal submatrix $\tilde{\boldsymbol{U}}$. In an embodiment, the orthonormal submatrix $\tilde{\boldsymbol{U}}$ may be compressed into phi and psi angles.

In an embodiment, the precoder matrix may be decomposed into submatrices using a QR decomposition according to the equation $\boldsymbol{W} = \tilde{\boldsymbol{Q}}\tilde{\boldsymbol{R}}$, and the submatrices comprise an orthonormal matrix $\tilde{\boldsymbol{Q}}$ with a last row comprising complex values and an upper triangular matrix $\tilde{\boldsymbol{R}}$ with a diagonal comprising values which are real and positive.

In an embodiment, the compressed precoder data may comprise an orthonormal submatrix **Q** where the last row contains only real and positive numbers, and an upper triangular submatrix **R** with complex elements.

According to another aspect there is provided a station device for receiving compressed and quantised precoder data from an access point as part of a trigger-based uplink data communication of a wireless network, the station device configured to receive compressed precoder data corresponding to one or more compressed submatrices of a decomposed precoder matrix, decompress the one or more submatrices, and recompose the precoder matrix for use in the trigger-based uplink data communication. The station device may be configured to transmit a null data packet to the access point in response to a trigger received from the access point prior to receiving the compressed precoder data.

In an embodiment, the station device may be configured to: receive compressed precoder data comprising a set of angles corresponding to a compressed orthonormal submatrix **U**; decompress the orthonormal submatrix **U** using one or more Givens rotations.

In an embodiment, the station device may be configured to: receive compressed precoder data comprising diagonal values of a diagonal submatrix **S**; decompress diagonal submatrix **S**; and recompose the precoder matrix for use by the station in the trigger-based uplink data communication using both decompressed orthonormal submatrix **U** and decompressed diagonal submatrix **S**.

In an embodiment, submatrix **U** may be computed according to the equation $\boldsymbol{U} = \tilde{\boldsymbol{U}}\boldsymbol{\Theta}^{H}$, where $\tilde{\boldsymbol{U}}$ is an orthonormal matrix, and $\boldsymbol{\Theta}^{H}$ is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\tilde{\boldsymbol{U}}$ and the station device may be configured to: receive compressed precoder data comprising a set of angles θ corresponding to the compressed diagonal submatrix **Θ;** and recompose the precoder matrix for use by the station in the trigger-based uplink data communication using decompressed orthonormal submatrix **U**, decompressed diagonal submatrix **S** and decompressed diagonal submatrix **Θ**.

In an embodiment, the station device may be configured to: receive compressed precoder data comprising a set of phi and psi angles corresponding to the complex elements of submatrix **Q**, quantized real diagonal values of an upper triangular matrix **R**, and quantized non-zero complex off-diagonal values of the upper triangular matrix **R**; and recompose a precoder matrix W for use by the station in the trigger-based uplink data communication by recomposing W from matrices **Q** and **R** obtained by

performing one or more Givens rotations to obtain orthonormal matrix **Q**, and recreating **R** from the quantized diagonal values and non-zero off-diagonal values of **R**.

In an embodiment, the station device is configured to: receive precoder data comprising a set of phi and psi angles corresponding to the complex elements of submatrix **Q** with a real last row, quantized complex diagonal values of an upper triangular matrix **R**, and quantized complex non-zero off-diagonal values of the upper triangular matrix **R**; and recompose a precoder matrix **W** for use by the station in the trigger-based uplink data communication using matrices **Q** and **R** obtained by performing one or more Givens rotations to obtain orthonormal matrix **Q** and recreating **R** from the quantized non-zero diagonal values of **R**.

According to another aspect there is provided an access point for providing compressed precoder data to one or more station devices as part of a trigger-based uplink data communication of a wireless network, the access point configured to: decompose a precoding matrix, calculated for each of the one or more station devices for use in the trigger-based uplink data communication, into a plurality of submatrices; compress a selection of the plurality of submatrices for including in the compressed precoder data; and transmit the compressed precoder data to the one or more station devices.

In an embodiment, the precoding matrix may be decomposed into submatrices using singular value decomposition and the compressed precoder data comprises at least a compressed orthonormal matrix **U**.

In an embodiment, the precoding matrix may be decomposed using QR decomposition and the compressed precoder data comprises at least a set of phi and psi angles, and quantized diagonal values of an upper triangular submatrix **R**.

BRIEF DESCRIPTION OF THE FIGURES

The present disclosure will now be described by way of example with reference to the accompanying drawings. In the drawings:

Fig. 1 illustrates a suggested procedure for precoded UL Trigger-based PPDU traffic.

Fig. 2 shows a graph which illustrates the gains that can be achieved by using an advanced precoder in precoded UL MU-MIMO data communications.

Fig. 3 shows a graph plotting packet error rate (PER) against signal to noise ratio (SNR) in decibels for each of a plurality of precoder types and various compression methods.

Fig. 4 shows a graph plotting packet error rate (PER) against signal to noise ratio (SNR) in decibels for each of three different compression bits combinations.

Fig. 5 shows a table illustrating the compression benefit from the above described SVD based method with compressed **U** and **S** transmitted as feedback.

Fig. 6 shows a table illustrating the compression benefit from the above described SVD based method with compressed **U** transmitted as feedback.

DETAILED DESCRIPTION OF THE INVENTION

Previously, UL precoding has not been used in the case of TB PPDUs. By adding this proposed process to IEEE 802.11 data communications the overall UL throughput would increase. Fig. 1 illustrates one suggested procedure for precoded UL Trigger-

based PPDU traffic and shows a horizontal line for each apparatus involved and a block on each line representing an action/process step carried out by said apparatus. The steps of the process occur from left to right along the lines. As can be seen, the AP 102 first triggers NDP transmission 104 from one or more STAs 106a, 106b, 106c. The STAs then each transmit their respective NDPs 108. Based on the received NDP(s), the channel from each STA can be estimated and precoder parameters are calculated by the AP 102 for each STA 106a-c. Then, a new trigger frame comprising Triggering Data and a Beamformer Report (BFR) 110 is transmitted by the AP 102 to the STA(s) 106a-c. This trigger frame comprises the specific precoder required by each STA 106a-c to be used in a following UL transmission. The STAs 106a-c are then able to send their beamformed UL data 112a-c to the AP 102. The AP 102 then responds to each STA 106a-c with a Block Acknowledgement frame 114.

It should be recognized that there may be other protocols developed to implement the process described herein. For example, the packet 110 may be divided into two different packets – one for providing the precoder, then a later one for triggering the STAs. The details of the protocol used are not important, the options described here are merely examples. The essence of the proposed method is not the protocol but the compression and quantization of the precoder itself.

Different precoding approaches may be used to implement the UL precoding. For SU-MIMO, the precoder can be computed in a straight-forward manner using Single Value Decomposition (SVD) of the channel matrix. For MU-MIMO, using the per-STA precoder yields a performance improvement but this is limited. Superior MU-MIMO precoders can be derived as described, for example, in doc IEEE 802.11-23/0027r1 submitted to UHR SG group by MaxLinear at IEEE: UL MU-MIMO Precoding; Sigurd Schelstraete; 17 January 2023; Uplink MU MIMO Improvements; from https://mentor.ieee.org/802.11/documents?is_dcn=27&is_group=0uhr.

Fig. 2 illustrates the gains that can be achieved by using an advanced precoder. Specifically, figure 2 shows the PER as a function of the SNR for a signal without precoding 202 (open-loop), a signal with per STA precoding 204, a signal using precoder algorithm #1 206 and a signal using precoder algorithm #2 208. It can easily be seen that UL precoder algorithm #2 208 and UL precoder algorithm #1 206 are better than not using a precoder 202 (i.e. open loop), by 8dB and 9dB, respectively. Furthermore, the two algorithms are both much better than using a per-STA precoder 204. The specifics of each algorithm are not described herein as this information is beyond the scope of this patent.

Though several feedback schemes were defined in the IEEE Standard 802.11n, the following IEEE Standard 802.11ac removed several schemes and only the compressed feedback scheme is now supported. The compression schemes are carried out by first generating a matrix **V** with dimensions (N_r, N_c) and orthonormal columns.

The Decomposition has the following form, taken from IEEE 802.11n:

$$\boldsymbol{V} = \prod_{i}^{min(N_c,N_r-1)} \left[\boldsymbol{D}_i\left(1_{i-1}, e^{j\phi_{i,i}} \ldots, e^{j\phi_{N_r-1,i}}, 1\right) \prod_{l=i+1}^{N_r} \boldsymbol{G}_{l,i}^{T}\left(\psi_{l,i}\right) \right] \tilde{\boldsymbol{I}}_{N_r \times N_c}$$

Where:

$$\boldsymbol{D}_i\left(1_{i-1}, e^{j\phi_{i,i}} \ldots, e^{j\phi_{N_r-1,i}}, 1\right) = \begin{bmatrix} \boldsymbol{I}_{i-1} & 0 & \ldots & \ldots & 0 \\ 0 & e^{j\phi_{i,i}} & 0 & \ldots & 0 \\ \vdots & 0 & \ddots & 0 & 0 \\ \vdots & \vdots & 0 & e^{j\phi_{N_r-1,i}} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\boldsymbol{G}_{l,i}(\psi) = \begin{bmatrix} \boldsymbol{I}_{i-1} & 0 & 0 & 0 & 0 \\ 0 & cos(\psi) & 0 & sin(\psi) & 0 \\ 0 & 0 & \boldsymbol{I}_{l-i-1} & 0 & 0 \\ 0 & -sin(\psi) & 0 & cos(\psi) & 0 \\ 0 & 0 & 0 & 0 & \boldsymbol{I}_{N_r-1} \end{bmatrix}.$$

The angles phi φ and psi ψ are then quantized according to one of a plurality of values specified in the standard. The number of bits per angle are denoted as b_φ and b_ψ.

There are proposed herein a number of potential compression schemes and methods for implementation of UL precoding. These benefit from not requiring adaptations to hardware already used in order to be implemented, or requiring minimal adaptations. The general ideas will now be discussed followed by some example embodiments.

Typically, a beamformee computes the precoder, which is an orthonormal matrix, using, for example, an SVD on the channel matrix. The precoder matrix is then compressed and fed back to the beamformer. In downlink MU-MIMO the access point can compute a completely different precoder (e.g. Pseudo-Inverse, PINV precoder) but doesn't need to deliver it to the station device. Additionally, there may be a long time between transmitting the precoder and the beamformed transmission.

However, there are important differences between the typical case and the UL scenario being considered herein.

Firstly, the access point computes the precoder and then must deliver it to the station device, but in the case of UL MU-MIMO this precoder isn't necessarily an orthonormal matrix. Further, the columns aren't necessarily normalized. This means that the existing explicit compression isn't applicable.

Secondly, there is a need to reduce the overhead as much as possible and the precoder data is possibly larger than the typical downlink case. Therefore, there is a question of how to do this, especially if the precoder isn't orthonormal and the existing methods don't work.

Thirdly, the access point may deliver the precoder together with the Trigger Frame and the station device would have to respond within SIFS (if the precoder is delivered with the Trigger Frame, the STA has to prepare its UL PPDU within SIFS and that would include the precoder). There is therefore a need to show that a station device can prepare precoding on time. Further, the access point should deliver a continuous precoder, which is unlike traditional sounding procedures.

Accordingly, there is proposed herein a method to compress the UL precoding matrices according to various example embodiments based on existing compression schemes (e.g. Givens matrices). It is not mandatory to use an orthonormal precoder for single user transmission, but it's usually the case. The method proposed herein can also be used to compress a non-orthonormal precoding matrix. In DL precoding (SU or MU) and in non-triggered-based UL precoding, the feedback is the channel, not the precoder itself. In these cases, the channel is represented as an orthonormal matrix.

There is also a need to allow the access point to maintain continuity of the precoder in the frequency domain. The proposed method achieves this and in some cases this requires the last row of the orthonormal matrix to be complex.

It has been noticed that the precoder is not sensitive to a right-multiplication by a unitary matrix. Therefore, it is possible to decompose any given precoder using SVD:

$\mathbf{W} = \mathbf{USV}^{\mathrm{H}}$, where $\mathbf{W}$ is the precoder matrix, and $\mathbf{U}$, $\mathbf{S}$, and $\mathbf{V}^{\mathrm{H}}$ are matrices provided as a result of decomposing $\mathbf{W}$ using SVD.

It has also been noticed that the precoder can be transmitted to the station device by feedback of only **U** and **S**. Since **U** is orthonormal and **S** is diagonal with real and positive entries, then it is possible to use the compression methods already defined in the standard with minimal changes in order to feedback the precoder.

It has also been noticed that as an alternative to SVD it is also possible to perform a QR decomposition of the precoder matrix **W**.

Accordingly, there is proposed herein a method for providing compressed and quantized precoder data to one or more station devices as part of a trigger-based uplink data communication of a wireless network. The method comprises calculating at the access point a precoding matrix for each of the one or more station devices, decomposing the precoding matrix of each station device into a plurality of submatrices and forming compressed precoder data from a selection of the plurality of submatrices, and transmitting the compressed precoder data to each of the one or more station devices. By the phrase a selection of submatrices it is meant that not all of the submatrices which are formed when the precoder matrix is decomposed are used to form the compressed precoder data. This is one way in which the precoder data which needs to be transmitted to the station devices can be reduced in size. Prior to calculating precoding matrices, the proposed method may comprise triggering by the access point each of the one or more station devices to transmit a sounding null data packet to the access point.

Below are described some example embodiments of the proposed method with the above-described aspects used to achieve the desired outcome of compressed uplink precoding. All embodiments below describe a compression method for a not-necessarily orthonormal precoding matrix for triggered UL MU-MIMO with BF. This is common to all embodiments, but the differences between them are described in the detailed description that follows.

The precoder data may be comprised within the trigger frame, transmitted along with it or within a separate PPDU. That is, transmission of the precoder may be done with the trigger frame, where it is transmitted after the trigger but in the same PPDU. Alternatively, the transmission of the precoder may be within the trigger frame, where it is transmitted as part of the content of the trigger frame. As a third option, the precoder data may be transmitted within a separate, prior PPDU than that used for the transmission of the trigger frame.

In a first embodiment there is provided a method which comprises SVD based precoder generation with reduced feedback size comprising the real last row of submatrix **U**.

In this embodiment the precoder **W** is decomposed using SVD. The precoder matrix is decomposed into submatrices where the submatrices comprise an orthonormal matrix, $\widetilde{\boldsymbol{U}}$, a diagonal matrix with real positive values, $\widetilde{\boldsymbol{S}}$, and a unitary matrix $\widetilde{\boldsymbol{V}}^{H}$. The output matrices **U** and **S** are then compressed while maintaining the last row values of **U** which are real and the diagonal values of **S** which are complex. This method may be defined according to the following steps.

Given a precoder matrix **W** with dimensions $(\mathbf{N_r}, \mathbf{N_c})$ compute the SVD decomposition according to the equation:

$$\boldsymbol{W} = \widetilde{\boldsymbol{U}}_{N_r \times N_c} \widetilde{\boldsymbol{S}}_{N_c \times N_c} \widetilde{\boldsymbol{V}}^{H}_{N_c \times N_c}.$$

It is possible to then denote θ_i and $\boldsymbol{\Theta}$ according to:

$$\theta_i = angle\left(\widetilde{\boldsymbol{U}}_{N_r,i}\right),\ \boldsymbol{\Theta} = \begin{bmatrix} e^{j\cdot\theta_1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & e^{j\cdot\theta_{N_c}} \end{bmatrix}.$$

To ensure there is phase continuity it is necessary to then compute:

$$\boldsymbol{U} = \tilde{\boldsymbol{U}}\boldsymbol{\Theta}^{\boldsymbol{H}}, \boldsymbol{S} = \boldsymbol{\Theta}\tilde{\boldsymbol{S}}.$$

Thus, $\tilde{\boldsymbol{U}}$ is the essence of the precoding matrix, and **U** is $\tilde{\boldsymbol{U}}$ with a maintained last row of real numbers. $\tilde{\boldsymbol{S}}$ can be thought of as a "matrix of gains" or as the singular values of the precoder matrix or a matrix of singular values. And **S** can thus be considered as a matrix of complex gains.

The final step is to compress and quantize **U** in an identical manner to the compressed BF procedure (e.g. using Givens) and real/imaginary components of **S**. The compressed precoder data thus comprises an orthonormal submatrix **U** where the last row contains only real and positive numbers, and only the diagonal elements of the complex submatrix **S**. The orthonormal submatrix **U** may be compressed into phi and psi angles. The angles phi and psi may be quantized. The diagonal elements of the submatrix **S** may be quantized using 2s complement.

The compressed precoder data may therefore comprise an orthonormal submatrix **U** where the last row contains only real and positive values, the diagonal elements of the submatrix $\tilde{\boldsymbol{S}}$, and a set of angles derived from the last row of **U**. However, the orthonormal submatrix **U** may be compressed into phi and psi angles and the diagonal elements of the submatrix $\tilde{\boldsymbol{S}}$ may also be compressed.

The angles phi and psi, the diagonal elements of the submatrix $\tilde{\boldsymbol{S}}$ and the set of angles θ_i may all be quantized, though the number of bits used to quantize phi, psi, and theta may be different.

The submatrix **U** may be computed according to the equation:

$$\boldsymbol{U} = \tilde{\boldsymbol{U}}\boldsymbol{\Theta}^{\boldsymbol{H}},$$

where $\tilde{\boldsymbol{U}}$ is an orthonormal matrix, $\boldsymbol{\Theta}^{H}$ is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\tilde{\boldsymbol{U}}$, and the matrix $\boldsymbol{U}$ is an orthonormal matrix with real and positive elements in the last row.

The submatrix **S** may be computed according to the equation:

$$\boldsymbol{S} = \boldsymbol{\Theta}\tilde{\boldsymbol{S}},$$

where **S** is a diagonal complex matrix, $\tilde{\boldsymbol{S}}$ is a diagonal real and positive matrix, and **Θ** is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\tilde{\boldsymbol{U}}$.

The compressed precoder data may thus comprise an orthonormal submatrix $\tilde{\boldsymbol{U}}$. The orthonormal submatrix $\tilde{\boldsymbol{U}}$ may be compressed into phi and psi angles. The angles phi and psi may also be quantized.

In a second embodiment there is provided a method which comprises SVD based precoder generation with reduced feedback size comprising the real last row of submatrix **U** and real values of **S**.

This embodiment is similar to the first example embodiment described above. The difference here is that instead of computing $\mathbf{S} = \boldsymbol{\Theta}\tilde{\mathbf{S}}$, the feedback comprises angles $\boldsymbol{\theta_i}$ and the real SNR $\tilde{\mathbf{S}}$. The compression of $\tilde{\mathbf{S}}$ is alternatively carried out using the existing SNR compression defined in the standard. The quantization of $\boldsymbol{\theta_i}$ is carried out using the same method as used for the compressed angles, which ensures that phase continuity is achieved.

In a third embodiment there is described a method which comprises SVD based precoder generation with reduced feedback size comprising only submatrix $\widetilde{\boldsymbol{U}}$.

In this embodiment the precoder **W** is also decomposed using SVD. However, in this embodiment the feedback only comprises the matrix $\widetilde{\boldsymbol{U}}$ (last row is complex).

The following steps further define this embodiment of the method. Given a precoder **W** with dimensions $(\mathbf{N_r}, \mathbf{N_c})$ the first step is to compute the SVD decomposition according to the following equation:

$$\boldsymbol{W} = \widetilde{\boldsymbol{U}}_{N_r \times N_c} \widetilde{\boldsymbol{S}}_{N_c \times N_c} \widetilde{\boldsymbol{V}}^{H}_{N_c \times N_c}.$$

The next step is to use the method of compressed BF procedure using Givens rotations to find diagonal matrix $\boldsymbol{D_i}$ and a Givens rotation $\boldsymbol{G}^{T}_{l,i}(\boldsymbol{\psi_{l,i}})$ matrix, such that $\widetilde{\boldsymbol{U}}$ can be formulated according to the following equations:

$$\widetilde{\boldsymbol{U}} = \prod_{i}^{min(N_c, N_r-1)} \left[\boldsymbol{D}_i \left(1_{i-1}, e^{j\phi_{i,i}} \ldots, e^{j\phi_{N_r-1,i}}, e^{j\phi_{N_r,i}}\right) \prod_{l=i+1}^{N_r} \boldsymbol{G}^{T}_{l,i}(\psi_{l,i}) \right] \widetilde{\boldsymbol{I}}_{N_r \times N_c},$$

$$\widetilde{\boldsymbol{I}}_{N_r \times N_c} = \begin{bmatrix} \boldsymbol{I}_{N_c} \\ \hline \boldsymbol{0}_{N_r - N_c \times N_c} \end{bmatrix}$$

where $\boldsymbol{\psi_{l,i}}$ are the plane rotation angles, $\boldsymbol{\phi_{j,i}}$ are angles due to the complex nature of the matrix $\widetilde{\boldsymbol{U}}$, Nr is the number of rows in the precoder matrix, and Nc is the number of columns in the precoder matrix, $\widetilde{\boldsymbol{I}}_{N_r \times N_c}$ is an identity matrix padded with 0s to fill the additional rows or columns when $N_r \neq N_c$. The term $\boldsymbol{\phi_{N_r,i}}$ in $\boldsymbol{D}_i$ is introduced to ensure phase continuity, which is an addition to the Givens rotations as defined in IEEE 802.11 standards.

The next step is to quantize the values of $\boldsymbol{\psi_{i,j}}$ and $\boldsymbol{\phi_{k,l}}$ using the method for Quantization of angles as defined in IEEE 802.11 standards and for example, as detailed in Table 9-92 of IEEE P802.11-REVme D4.2.

Therefore, in this example embodiment, the precoder data comprises a set of angles derived from the diagonal values of a matrix $\boldsymbol{D}_i$, where $\boldsymbol{D}_i$ is defined as:

$$\boldsymbol{D}_i \left(1_{i-1}, e^{j\phi_{i,i}} \ldots, e^{j\phi_{N_r-1,i}}, e^{j\phi_{N_r,i}}\right)$$

and is part of a Givens operation as defined in any of the IEEE family of standards such as 802.11n or 802.11ac or 802.11ax or 802.11be.

More concretely, the following example from the IEEE 802.11 standard, of Givens rotations for a 4x2 orthonormal matrix, denoted as V, where the last row is real numbers:

$$V = \begin{bmatrix} e^{j\phi_{11}} & 0 & 0 & 0 \\ 0 & e^{j\phi_{21}} & 0 & 0 \\ 0 & 0 & e^{j\phi_{31}} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} cos\,\psi_{21} & sin\,\psi_{21} & 0 & 0 \\ -sin\,\psi_{21} & cos\,\psi_{21} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^{T} \times \begin{bmatrix} cos\,\psi_{31} & 0 & sin\,\psi_{31} & 0 \\ 0 & 1 & 0 & 0 \\ -sin\,\psi_{31} & 0 & cos\,\psi_{31} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^{T}$$
$$\times \begin{bmatrix} cos\,\psi_{41} & 0 & 0 & sin\,\psi_{41} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -sin\,\psi_{41} & 0 & 0 & cos\,\psi_{41} \end{bmatrix}^{T}$$

$$\times\begin{bmatrix}1&0&0&0\\0&e^{j\phi_{22}}&0&0\\0&0&e^{j\phi_{32}}&0\\0&0&0&1\end{bmatrix}\times\begin{bmatrix}1&0&0&0\\0&\cos\psi_{32}&\sin\psi_{32}&0\\0&-\sin\psi_{32}&\cos\psi_{32}&0\\0&0&0&1\end{bmatrix}^T\times\begin{bmatrix}1&0&0&0\\0&\cos\psi_{42}&0&\sin\psi_{42}\\0&0&1&0\\0&-\sin\psi_{42}&0&\cos\psi_{42}\end{bmatrix}^T\times\begin{bmatrix}1&0\\0&1\\0&0\\0&0\end{bmatrix}$$

The required changes to support an orthonormal matrix with a complex last row are shown in the following equations inside curved brackets:

$$V=\begin{bmatrix}e^{j\phi_{11}}&0&0&0\\0&e^{j\phi_{21}}&0&0\\0&0&e^{j\phi_{31}}&0\\0&0&0&\{e^{j\phi_{41}}\}\end{bmatrix}\times\begin{bmatrix}\cos\psi_{21}&\sin\psi_{21}&0&0\\-\sin\psi_{21}&\cos\psi_{21}&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}^T\times\begin{bmatrix}\cos\psi_{31}&0&\sin\psi_{31}&0\\0&1&0&0\\-\sin\psi_{31}&0&\cos\psi_{31}&0\\0&0&0&1\end{bmatrix}^T$$

$$\times\begin{bmatrix}\cos\psi_{41}&0&0&\sin\psi_{41}\\0&1&0&0\\0&0&1&0\\-\sin\psi_{41}&0&0&\cos\psi_{41}\end{bmatrix}^T$$

$$\times\begin{bmatrix}1&0&0&0\\0&e^{j\phi_{22}}&0&0\\0&0&e^{j\phi_{32}}&0\\0&0&0&\{e^{j\phi_{42}}\}\end{bmatrix}\times\begin{bmatrix}1&0&0&0\\0&\cos\psi_{32}&\sin\psi_{32}&0\\0&-\sin\psi_{32}&\cos\psi_{32}&0\\0&0&0&1\end{bmatrix}^T\times\begin{bmatrix}1&0&0&0\\0&\cos\psi_{42}&0&\sin\psi_{42}\\0&0&1&0\\0&-\sin\psi_{42}&0&\cos\psi_{42}\end{bmatrix}^T\times\begin{bmatrix}1&0\\0&1\\0&0\\0&0\end{bmatrix}$$

All three of the embodiments detailed above use SVD to decompose the precoder matrix **W**. However, there are other equally applicable decomposition processes.

In a fourth embodiment there is provided a method which comprises QR based precoder feedback generation comprising the real diagonal values of $\widetilde{\boldsymbol{R}}$. In this embodiment the notation is as follows: $\widetilde{\boldsymbol{Q}}$ = all complex last row; $\widetilde{\boldsymbol{R}}$ = real positive diagonal; Q = real last row; R = complex diagonal.

In this embodiment the precoder matrix **W** is decomposed using QR decomposition. QR decomposition is the decomposition of a matrix into a product of an orthonormal matrix $\widetilde{\boldsymbol{Q}}$ and an upper triangular matrix $\widetilde{\boldsymbol{R}}$. If **W** is invertible, then the factorization is unique if the diagonal elements of $\widetilde{\boldsymbol{R}}$ are required to be positive. If instead **W** is a complex square matrix, then there is a decomposition where $\widetilde{\boldsymbol{Q}}$ is a unitary matrix.

In this case the requirements are that $\widetilde{\boldsymbol{Q}}$ has complex values in its last row, and $\widetilde{\boldsymbol{R}}$ is an upper triangular with real positive diagonal values. The diagonal values of $\widetilde{\boldsymbol{R}}$ can then be quantized separately. That is, the diagonal values are guaranteed to be both real and positive only.

Thus, there is provided a method where the precoder matrix is decomposed into submatrices using a QR decomposition according to the equation:
$\boldsymbol{W}=\widetilde{\boldsymbol{Q}}\widetilde{\boldsymbol{R}}$ and the submatrices comprise an orthonormal matrix $\widetilde{\boldsymbol{Q}}$ with a last row comprising complex values and an upper triangular matrix $\widetilde{\boldsymbol{R}}$ with a diagonal comprising values which are real and positive.

This method may be defined according to the following steps.

Given a precoder matrix **W** with dimensions $(\mathbf{N_r}, \mathbf{N_c})$, find the diagonal matrices $\mathbf{D_i}$, the Givens rotation matrices $\boldsymbol{G}_{l,i}^{T}(\boldsymbol{\psi}_{l,i})$, and an upper triangular matrix $\widetilde{\boldsymbol{R}}$ with real and positive diagonal values, such that **W** can be formulated according to the following equation:

$$\boldsymbol{W} = \prod_{i}^{min(N_c,N_r-1)} \left[\boldsymbol{D}_i\left(1_{i-1}, e^{j\phi_{i,i}} \ldots, e^{j\phi_{N_r,i}}\right) \prod_{l=i+1}^{N_r} \boldsymbol{G}_{l,i}^{T}\left(\psi_{l,i}\right) \right] \widetilde{\boldsymbol{R}}$$

With $\widetilde{\boldsymbol{Q}}$ defined as:

$$\widetilde{\boldsymbol{Q}} = \prod_{i}^{min(N_c,N_r-1)} \left[\boldsymbol{D}_i\left(1_{i-1}, e^{j\phi_{i,i}} \ldots, e^{j\phi_{N_r,i}}\right) \prod_{l=i+1}^{N_r} \boldsymbol{G}_{l,i}^{T}\left(\psi_{l,i}\right) \right]$$

The term $\boldsymbol{\phi}_{\boldsymbol{N_r,i}}$ in $\boldsymbol{D}_i$ is introduced to ensure phase continuity, which is a corresponding addition to the Givens rotations as defined in IEEE 802.11 family of standards (including 802.11n, 802.11ac, 802.11ax, 802.11be and 802.11bn). The term $\widetilde{\boldsymbol{R}}$ is also a minor adaptation to the Givens rotation, which arises from the fact that **W** may not be orthonormal.

The next step is to perform quantization of the angles $\boldsymbol{\psi_{i,j}}$ and $\boldsymbol{\phi_{k,l}}$ according to the Quantization of angles procedure defined in the IEEE standard 802.11, for example, under Compressed Beamforming frame format as mentioned above. The diagonal entries of $\widetilde{\boldsymbol{R}}$are also quantized, along with any non-zero off-diagonal entries of $\widetilde{\boldsymbol{R}}$, according to the non-compressed beamforming procedure in the 802.11 standard. By off-diagonal entries it is meant to include all elements of the matrix except those on the diagonal.

The submatrix **Q** may be computed according to the equation: $\boldsymbol{Q} = \widetilde{\boldsymbol{Q}}\boldsymbol{\Theta}^{H}$, where $\widetilde{\boldsymbol{Q}}$ is an orthonormal matrix, $\boldsymbol{\Theta}^{H}$ is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\widetilde{\boldsymbol{Q}}$, and the matrix $\boldsymbol{Q}$ is an orthonormal matrix with real and positive elements in the last row.

The submatrix **R** may be computed according to the equation: $\boldsymbol{R} = \boldsymbol{\Theta}\widetilde{\boldsymbol{R}}$. The method may also comprise the quantisation of the real and positive values of the diagonal of upper triangular matrix $\widetilde{\boldsymbol{R}}$. The method may also comprise quantisation of all non-zero off-diagonal values of $\widetilde{\boldsymbol{R}}$.

In a fifth embodiment there is described a method which comprises QR based precoder feedback generation comprising complex diagonal values of **R**.

In this embodiment the precoder matrix **W** is decomposed using QR, as in the previous embodiment. However, in this embodiment **Q** has real values in its last row and the upper triangular matrix **R** has complex diagonal values. Therefore, there is provided a method where the compressed precoder data comprises an orthonormal submatrix **Q** with the last row containing only real and positive numbers, and an upper triangular submatrix **R** with complex elements. This method may be defined according to the following steps.

Given a precoder matrix **W** with dimensions **(N_r, N_c)**, find the diagonal matrices $\mathbf{D_i}$, Givens rotation matrices $\boldsymbol{G_{l,i}^{T}}\left(\boldsymbol{\psi_{l,i}}\right)$, and an upper triangular matrix **R** with complex values in the diagonal and off-diagonal entries, such that **W** can be formulated according to the following equation:

$$\boldsymbol{W} = \prod_{i}^{min(N_c,N_r-1)} \left[\boldsymbol{D}_i\left(1_{i-1}, e^{j\phi_{i,i}} \ldots, e^{j\phi_{N_r-1,i}}, 1\right) \prod_{l=i+1}^{N_r} \boldsymbol{G}_{l,i}^{T}\left(\psi_{l,i}\right) \right] \boldsymbol{R}$$

The orthonormal submatrix **Q** may then be compressed into phi and psi angles. The next step is to perform quantization of the angles $\boldsymbol{\phi_{i,j}}$ and $\boldsymbol{\psi_{k,l}}$. For example, this may be done according to the compressed beamforming procedure defined in the IEEE

standard 802.11. The non-zero entries of **R** are also quantized. This may be done according to the non-compressed beamforming procedure defined in the IEEE standard 802.11. For example, they may be quantized using 2s compliment.

Therefore, there is provided a method where the precoder data comprises an orthonormal submatrix **Q**, and an upper triangular submatrix **R** with complex elements and real and positive values on its diagonal. The orthonormal submatrix **Q** may be compressed into phi and psi angles. The angles phi and psi may be quantized.

There is also provided herein a station device and access point configured to implement the method described above and all example embodiments. One benefit of the above method is that the hardware of the corresponding station devices and access points, or equivalent apparatus, are not required to be changed in order to implement the method. The devices simply need to be configured to execute the required method steps implemented at those devices.

There is therefore provided a station device for receiving compressed and quantised precoder data from an access point as part of a trigger-based uplink data communication of a wireless network. The station device is configured to receive compressed precoder data corresponding to one or more compressed submatrices of a decomposed precoder matrix, decompress the one or more submatrices, and recompose the precoder matrix for use in the trigger-based uplink data communication. The station device may be configured to transmit a null data packet to the access point in response to a trigger received from the access point prior to receiving the compressed precoder data.

As in this embodiment the communication event is an uplink beamformed trigger-based communication, the station device is responsible for receiving the compressed precoder data, having been compressed according to any of the above described embodiments, and process this in order to obtain the necessary precoder data for executing the beamformed uplink transmission.

In an embodiment, the station device is configured to receive compressed precoder data comprising a set of angles corresponding to a compressed orthonormal submatrix **U** and decompress the orthonormal submatrix **U** using one or more Givens rotations.

The station device may then be configured to receive the compressed precoder data also comprising diagonal values of a diagonal submatrix **S**, decompress the diagonal submatrix **S**, and recompose the precoder matrix for use by the station device in the trigger-based uplink data communication using both decompressed orthonormal submatrix **U** and decompressed diagonal submatrix **S**.

Where submatrix **U** is computed according to the equation $\boldsymbol{U} = \widetilde{\boldsymbol{U}}\Theta^{H}$ and $\widetilde{\boldsymbol{U}}$ is an orthonormal matrix and $\boldsymbol{\Theta}^{H}$ is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\widetilde{\boldsymbol{U}}$, the station device may also be configured to receive compressed precoder data comprising a set of angles θ corresponding to the compressed diagonal submatrix **Θ**, and recompose the precoder matrix for use by the station in the trigger-based uplink data communication using decompressed orthonormal submatrix **U**, decompressed diagonal submatrix **S** and decompressed diagonal submatrix **Θ**.

In an example embodiment, the station device may be configured to receive compressed precoder data comprising a set of phi and psi angles corresponding to the complex elements of submatrix **Q**, quantized real diagonal values of an upper triangular matrix **R**, and quantized non-zero complex off-diagonal values of the upper triangular matrix **R**. The station device may then recompose a precoder matrix **W** for use by the station in the trigger-based uplink data communication by recomposing **W** from matrices **Q** and **R** obtained by performing one or more Givens rotations to obtain orthonormal matrix **Q**, and recreating **R** from the quantized diagonal values and non-zero off-diagonal values of **R**.

in an example embodiment, the station device may be configured to receive precoder data comprising a set of phi and psi angles corresponding to the complex elements of submatrix **Q** with a real last row, quantized complex diagonal values of an upper

triangular matrix **R**, and quantized complex non-zero off-diagonal values of the upper triangular matrix **R**. Th station device may then be configured to recompose a precoder matrix **W** for use by the station in the trigger-based uplink data communication using matrices **Q** and **R** obtained by performing one or more Givens rotations to obtain orthonormal matrix **Q** and recreating **R** from the quantized non-zero diagonal values of **R**.

Similarly, there is provided an access point configured according to the necessary steps to be performed by the access point to implement the above described method of any embodiment.

Therefore, there is provided an access point for providing compressed precoder data to one or more station devices as part of a trigger-based uplink data communication of a wireless network. The access point is configured to decompose a precoding matrix, calculated for each of the one or more station devices for use in the trigger-based uplink data communication, into a plurality of submatrices. The access point is configured to then compress a selection of the plurality of submatrices for including in the compressed precoder data and then transmit the compressed precoder data to the one or more station devices.

In an embodiment, the precoding matrix may be decomposed into submatrices using singular value decomposition and the compressed precoder data may comprise at least a compressed orthonormal matrix **U**. The precoder data may additionally comprise a compressed submatrix **S** in the form of its diagonal values.

In an embodiment, the precoder data may comprise a compressed submatrix $\tilde{\boldsymbol{S}}$ using signal to noise ratio compression and a compressed angle set derived from quantisation of $\tilde{\boldsymbol{U}}$'s last row phases, θ_i.

When the precoding matrix is decomposed using QR decomposition, the compressed precoder data may comprise at least a set of phi and psi angles, and quantized diagonal values of an upper triangular submatrix **R**. The compressed precoder data may comprise quantized non-zero off-diagonal values of the upper triangular matrix **R**. The compressed precoder data may comprise quantized non-zero values of the upper triangular matrix **R**.

The methods outlined in the above-described embodiments using SVD based decomposition have been tested with simulated parameters. The simulation parameters are:

- 2 STAs with 4 Tx antennas, 3 SS and MCS 9
- TGnD NLOS Channel
- AP with 6 Rx antennas
- MMSE Equalizer

Fig. 3 shows a graph of packet error rate (PER) against signal to noise ratio (SNR) in decibels for each of algorithm #1 and #2 (as mentioned above in reference to figure 2), with feedback comprising **U** and **S**, or **U** only, as well as for full BF, non-BF, and BF per user options. The graph indicates the performance of each variation of the proposed method.

The line 302 (solid line) shows the simulated result using full BF. The line 304 (dashed line with square markers) shows the simulated result using SVD decomposition with BF algorithm #1 and feedback comprising **U** and **S**. The line 306 (solid line with circular markers) shows the simulated result using SVD decomposition with BF algorithm #1 and feedback comprising **U** only. The line 314 (solid line with cross markers) shows the simulated result with BF per user. The line 316 (solid line with diamond markers) shows the simulated result with no BF.

It can be seen in figure 3 that feeding back **U** and **S** for the precoder to the STAs represented by lines 304 and 310 preserves the performance and the proposed SVD method only results in a ~0.5dB of degradation when using **U** alone as shown by lines 306 and 312.

The methods outlined in the above-described embodiments using QR based decomposition have been tested with simulated parameters. The simulation parameters are:

- 2 STAs with 4 transmitting antennas, 4 SS and using MCS 9
- TGnD NLOS Channel
- AP with 8 receiving antennas
- MMSE Equalizer

Fig. 4 shows a graph of packet error rate (PER) as a function of signal to noise ratio (SNR) in decibels for each of three different compression bits combinations and one without compression.

The line 402 (dashed line with circle markers) shows the simulated result when compressing with (6, 4) bits. The line 404 (dotted line) shows the simulated result when compressing with (5, 3) bits. The line 406 (solid line) shows the simulated result when no compression is used. The line 408 (dashed line) shows the simulated result when compressing with (9, 7) bits.

It can be seen in the graph of figure 4 that compressing with (5,3) bits (line 404) loses only ~1dB in performance, whereas using compression with (9,7) bits (line 408) yields performance similar to no compression at all.

Three options are assumed for the precoder that the AP transmits to the STA. The first option is that the AP transmits the explicit matrix **W**. In this case there is no work for the STA, just multiply before transmission. The second option is that the AP QR-decomposes **W** and transmits the angles of compressed **Q** and an explicit **R**. The third option is that the AP SVD-decomposes **W** to $\mathbf{USV}^{H}$ and transmits the angles of compressed **U** and a compressed **S.**

Since the SVD based method is more complicated than the QR based method, it is assumed that meeting the timing requirements for the SVD based method will suffice also for the QR based method.

In the SVD based method, the STA gets the angles of matrix **U**, and in one embodiment the diagonal matrix **S**, from the AP. The STA therefore needs to decompress **U**. For this, multiple Givens rotations are used. For example, in a 4x4 system the matrix **U** is compressed into 12 angles – 6 Psi angles and 6 Phi angles. Therefore, the corresponding Givens matrices need to be generated and multiplied by.

Fig. 5 shows a table illustrating the compression benefit from the above described SVD based method with compressed **U** and a compressed **S** transmitted compared to non-compressed feedback being transmitted.

The first five columns 502 – Nr, Nc, N Phi, N Psi, and N theta – present various options for the size of the precoder matrix and the bits per compression angle to feedback. The next four columns 504 present the total number of bits needed after compression for each of the **W** size options where the real number requires either 3, 5, 6, or 8 bits. The following four columns 506 present the same information as the previous four columns but with no compression of the feedback. The next four columns 508 present the difference in bits of the total bits after compression vs the total bits without compression. It can be seen that the most bits saved per size option is for when the real number requires 8 bits. This number of bits saved is shown as a percentage in the final column 510.

The number of bits has been calculated as follows. The Bits Per Phi angle = Bits Per Real Number + 1. Bits Per Psi angle = Bits Per Real Number - 1. Bits Per Theta angle = Bits Per Real Number + 1. Bits Per **S** entry = Bits Per Real Number. Bits Per Non-Compressed entry = Bits Per Real Number.

Fig. 6 shows a table illustrating the compression benefit from the above described SVD based method with only compressed **U** transmitted compared to non-compressed feedback being transmitted.

The first four columns 602 – Nr, Nc, N Phi, and N Psi – present various options for the size of the precoder matrix and the bits per compression angle to feedback. The next four columns 604 present the total number of bits needed after compression for each of the **W** size options where the real number requires either 3, 5, 6, or 8 bits. The following four columns 606 present the same information as the previous four columns but with no compression of the feedback. The next four columns 608 present the difference in bits of the total bits after compression vs the total bits without compression. It can be seen that the most bits saved per size option is for when the real number requires 8 bits. The number of bits saved is shown as a percentage in the final column 610.

The number of bits has been calculated as follows. Bits Per Phi angle = Bits Per Real Number + 1. Bits Per Psi angle = Bits Per Real Number – 1. Bits Per Non-Compressed entry = Bits Per Real Number.

In an embodiment, the orthonormal submatrix **U** may be compressed into phi and psi angles. In an embodiment, the angles phi and psi may be quantized, and diagonal elements of the submatrix **S** may be quantized using 2s complement.

In an embodiment, the orthonormal submatrix U may be compressed into phi and psi angles and the diagonal elements of the submatrix $\tilde{S}$ may be compressed.

In an embodiment, the angles phi and psi, the diagonal elements of the submatrix $\tilde{S}$ and the set of angles θ_i may be quantized, where the number of bits used to quantize phi, psi, and theta may be different.

In an embodiment, the angles phi and psi may be quantized.

In an embodiment, the precoder data may comprise a set of angles derived from the diagonal values of a matrix D_i, where D_i is defined as: $D_i\left(1_{i-1}, e^{j\phi_{i,i}} \ldots, e^{j\phi_{N_r-1,i}}, e^{j\phi_{N_r,i}}\right)$ and requires corresponding adaptations to a Givens operation as defined in the IEEE 802.11 family of standards (including 802.11n, 802.11ac, 802.11ax, 802.11be and 802.11bn).

In an embodiment, the orthonormal submatrix **Q** may be compressed into phi and psi angles. In an embodiment, the angles phi and psi may be quantized, and non-zero elements of the submatrix **R** may be quantized using 2s complement.

In an embodiment, the submatrix **Q** may be computed according to the equation: $\boldsymbol{Q} = \widetilde{\boldsymbol{Q}}\boldsymbol{\Theta}^H$, where $\widetilde{\boldsymbol{Q}}$ is an orthonormal matrix, $\boldsymbol{\Theta}^H$ is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\widetilde{\boldsymbol{Q}}$, and the matrix $\boldsymbol{Q}$ is an orthonormal matrix with real and positive elements in the last row.

In an embodiment, the submatrix **R** may be computed according to the equation: $\boldsymbol{R} = \boldsymbol{\Theta}\widetilde{\boldsymbol{R}}$.

In an embodiment, the precoder data may comprise an orthonormal submatrix $\widetilde{\boldsymbol{Q}}$, and an upper triangular submatrix $\widetilde{\boldsymbol{R}}$ with complex elements and real and positive values on its diagonal.

In an embodiment, the orthonormal submatrix $\widetilde{\boldsymbol{Q}}$ may be compressed into phi and psi angles. In an embodiment, the angles phi and psi may be quantized.

In an embodiment, the method may comprise quantisation of the real and positive values of the diagonal of upper triangular matrix $\widetilde{\boldsymbol{R}}$.

In an embodiment, the method may comprise quantisation of all non-zero off-diagonal values of $\tilde{\boldsymbol{R}}$.

In an embodiment, there is provided an access point wherein the precoder data comprises a compressed submatrix **S** in the form of its diagonal values.

In an embodiment, there is provided an access point wherein the precoder data may comprise a compressed submatrix $\tilde{\boldsymbol{S}}$ using signal to noise ratio compression and a compressed angle set derived from quantisation of **U**'s last row phases, θ_i.

In an embodiment, there is provided an access point wherein the compressed precoder data may comprise quantized non-zero off-diagonal values of the upper triangular matrix **R**. In an embodiment, the compressed precoder data may comprise quantized non-zero values of the upper triangular matrix **R**.

The applicant hereby discloses in isolation each individual feature described herein and any combination of two or more such features, to the extent that such features or combinations are capable of being carried out based on the present specification as a whole in the light of the common general knowledge of a person skilled in the art, irrespective of whether such features or combinations of features solve any problems disclosed herein, and without limitation to the scope of the claims. The applicant indicates that aspects of the present disclosure may consist of any such individual feature or combination of features. In view of the foregoing description it will be evident to a person skilled in the art that various modifications may be made within the scope of the disclosure.

CLAIMS

1. A method for providing compressed and quantized precoder data to one or more station devices as part of a trigger-based uplink data communication of a wireless network, the method comprising:

calculating at an access point of the wireless network a precoding matrix for each of the one or more station devices;

decomposing the precoding matrix of each station device into a plurality of submatrices and forming compressed precoder data from a selection of the plurality of submatrices; and

transmitting the compressed precoder data to each of the one or more station devices.

2. The method according to claim 1, wherein the precoder matrix is decomposed using singular value decomposition, SVD, into submatrices where the submatrices comprise an orthonormal matrix, $\tilde{\boldsymbol{U}}$, a diagonal matrix with real positive values, $\tilde{\boldsymbol{S}}$, and a unitary matrix $\tilde{\boldsymbol{V}}^H$ according to the equation:

$$\mathbf{W} = \tilde{\mathbf{U}}_{N_r \times N_c} \tilde{\mathbf{S}}_{N_c \times N_c} \tilde{\mathbf{V}}^H_{N_c \times N_c}.$$

3. The method according to any preceding claim, wherein the compressed precoder data comprises an orthonormal submatrix **U** where the last row contains only real and positive numbers, and diagonal elements of the complex submatrix **S**.

4. The method according to any preceding claim, wherein the compressed precoder data comprises an orthonormal submatrix **U** where the last row contains only real and positive values, the diagonal elements of the submatrix $\tilde{\boldsymbol{S}}$ and a set of angles derived from the last row of **U**.

5. The method according to any of claims 2 to 4, wherein the submatrix **U** is computed according to the equation:

$$\boldsymbol{U} = \tilde{\boldsymbol{U}}\boldsymbol{\Theta}^H$$

where $\tilde{\boldsymbol{U}}$ is an orthonormal matrix, $\boldsymbol{\Theta}^H$ is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\tilde{\boldsymbol{U}}$, and the matrix $\boldsymbol{U}$ is an orthonormal matrix with real and positive elements in the last row.

6. The method according to any of claims 2 to 5, wherein the submatrix **S** is computed according to the equation:

$$\boldsymbol{S} = \boldsymbol{\Theta}\tilde{\boldsymbol{S}},$$

where **S** is a diagonal complex matrix, $\tilde{S}$ is a diagonal real and positive matrix, and **Θ** is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\tilde{\boldsymbol{U}}$.

7. The method according to any of claims 2 to 6, wherein the compressed precoder data comprises an orthonormal submatrix $\tilde{\boldsymbol{U}}$.

8. The method according to claim 7, wherein the orthonormal submatrix $\tilde{\boldsymbol{U}}$ is compressed into phi and psi angles.

9. The method according to claim 1, wherein the precoder matrix is decomposed into submatrices using a QR decomposition according to the equation $\boldsymbol{W} = \tilde{\boldsymbol{Q}}\tilde{\boldsymbol{R}}$, and the submatrices comprise an $N_r \times N_c$ orthonormal matrix $\tilde{\boldsymbol{Q}}$ with a last row comprising complex values and an upper triangular $N_c \times N_c$ matrix $\tilde{\boldsymbol{R}}$ with a diagonal comprising values which are real and positive.

10. The method according to claim 9, wherein the compressed precoder data comprises an orthonormal submatrix **Q** where the last row contains only real and positive numbers, and an upper triangular submatrix **R** with complex elements.

11. A station device for receiving compressed and quantised precoder data from an access point as part of a trigger-based uplink data communication of a wireless network, the station device configured to receive compressed precoder data corresponding to one or more compressed submatrices of a decomposed precoder matrix, decompress the one or more submatrices, and recompose the precoder matrix for use in the trigger-based uplink data communication.

12. The station device according to claim 11, wherein the station device is configured to:

receive compressed precoder data comprising a set of angles corresponding to a compressed orthonormal submatrix **U**;

decompress the orthonormal submatrix **U** using one or more Givens rotations.

13. The station device according to claim 12, wherein the station device is configured to:

receive compressed precoder data comprising diagonal values of a diagonal submatrix **S**;

decompress diagonal submatrix **S**; and

recompose the precoder matrix for use by the station in the trigger-based uplink data communication using both decompressed orthonormal submatrix **U** and decompressed diagonal submatrix **S**.

14. The station device according to claim 13, wherein submatrix **U** is computed according to the equation $\boldsymbol{U} = \widetilde{\boldsymbol{U}}\boldsymbol{\Theta}^{H}$, where $\widetilde{\boldsymbol{U}}$ is an orthonormal matrix, and $\boldsymbol{\Theta}^{H}$ is a diagonal matrix containing complex exponentials derived from the last row of the matrix $\widetilde{\boldsymbol{U}}$ and the station device is configured to:

receive compressed precoder data comprising a set of angles θ corresponding to the compressed diagonal submatrix **Θ;** and

recompose the precoder matrix for use by the station in the trigger-based uplink data communication using decompressed orthonormal submatrix **U**, decompressed diagonal submatrix **S** and decompressed diagonal submatrix **Θ**.

15. The station device according to claim 11, wherein the station device is configured to:

receive compressed precoder data comprising a set of phi and psi angles corresponding to the complex elements of submatrix **Q**, quantized real diagonal values of an upper triangular matrix **R**, and quantized non-zero complex off-diagonal values of the upper triangular matrix **R**; and

recompose a precoder matrix **W** for use by the station in the trigger-based uplink data communication by recomposing **W** from matrices **Q** and **R** obtained by performing one or more Givens rotations to obtain orthonormal matrix **Q**, and recreating **R** from the quantized diagonal values and non-zero off-diagonal values of **R**.

16. The station device according to claim 11, wherein the station device is configured to:

receive precoder data comprising a set of phi and psi angles corresponding to the complex elements of submatrix **Q** with a real last row, quantized complex diagonal values of an upper triangular matrix **R**, and quantized complex non-zero off-diagonal values of the upper triangular matrix **R**; and

recompose a precoder matrix **W** for use by the station in the trigger-based uplink data communication using matrices **Q** and **R** obtained by performing one or more Givens rotations to obtain orthonormal matrix **Q** and recreating **R** from the quantized non-zero diagonal values of **R**.

17. An access point for providing compressed precoder data to one or more station devices as part of a trigger-based uplink data communication of a wireless network, the access point configured to:

decompose a precoding matrix, calculated for each of the one or more station devices for use in the trigger-based uplink data communication, into a plurality of submatrices;

compress a selection of the plurality of submatrices for including in the compressed precoder data; and

transmit the compressed precoder data to the one or more station devices.

18. An access point according to claim 17, wherein the precoding matrix is decomposed into submatrices using singular value decomposition and the compressed precoder data comprises at least a compressed orthonormal matrix **U,** or
5 the precoding matrix is decomposed using QR decomposition and the compressed precoder data comprises at least a set of phi and psi angles, and quantized diagonal values of an upper triangular submatrix **R**.