Adaptive codebook-based channel prediction and interpolation for multiuser multiple-input multiple-output–orthogonal frequency division multiplexing systems

J. Chang1 I.T. Lu1 Y.X. Li2
1Department of ECE, Polytechnic Institute of New York University, Brooklyn, NY 11201, USA
2InterDigital Communications LLC, King of Prussia, PA 19406, USA
E-mail: changjiang.cn@gmail.com

Abstract: In multiple-input multiple-output–orthogonal frequency division multiplexing (MIMO–OFDM) communications, the channel state information (CSI) of the forward link at each subcarrier is needed for precoder design at the transmitter to achieve the maximal diversity and/or multiplexing gains. In frequency division duplex (FDD) systems, the CSI needs to be estimated at the receivers and fed back to the transmitters. Owing to the limited network resources, there will be CSI feedback errors due to quantisation, delay and clustering (where one CSI feedback is used to represent a cluster of adjacent subcarriers for feedback reduction). Consequently, the system performance degrades and the gains expected from using MIMO diminish. To mitigate this performance degradation, an adaptive codebook-based CSI prediction and interpolation scheme is proposed for multiuser MIMO–OFDM systems. In this scheme, geodesic CSI prediction is employed at the receiver to mitigate the feedback delay effect and geodesic CSI interpolation is performed at the transmitter to mitigate the clustering feedback effect. Since the performance gain assumed by the CSI prediction and interpolation is limited by the low-resolution CSI quantisation, an adaptive codebook scheme is proposed to be used to support the CSI prediction and interpolation. Simulation results show that the proposed scheme is effective in mitigating the performance loss due to quantisation, feedback delay and clustering feedback.

1 Introduction

Multiple-input multiple-output (MIMO) and orthogonal frequency division multiplexing (OFDM) have been adopted by many modern wireless broadband standards, such as 3GPP long term evolution (LTE) [1], IEEE 802.16m (WiMAX) [2] etc. MIMO technique can provide high spectral efficiency by exploiting the multipath features in the spatial dimension. OFDM can also provide a better spectral efficiency by using overlapped orthogonal subcarriers for parallel transmission. In addition, the long symbol duration and the usage of cyclic prefix enable OFDM to combat severe frequency selective fading effectively without using complex equalisation techniques.

In order to achieve the full merits of MIMO–OFDM communications, channel state information (CSI) needs to be known at the transmitter. In frequency division duplex (FDD) systems, one widely used solution is to estimate the CSI at the receiver and feedback the quantised CSI to the transmitter. A good overview of the limited feedback techniques can be found in [3].

Three main issues (quantisation errors, feedback delays and clustering feedback) need to be considered in the design of a limited feedback scheme. Quantisation error is introduced by quantising the infinite precision CSIs with finite codewords. CSI quantisation error may cause severe system performance degradation and thus high-resolution CSI quantisation techniques are investigated (e.g. see [4–6]).

The feedback delay is inevitable in practical MIMO systems due to the transceiver processing, propagation delay and network delay. Using the outdated CSI for transmit processing will definitely cause system performance degradation. One prevalent solution to mitigate the feedback delay is to use CSI prediction. In terms of CSI models, some CSI prediction techniques are model based [7, 8] where the channel is modelled as a function of some physical parameters (e.g. the sum-of-sinusoids channel model). Other CSI prediction techniques are non-model based [9–12] where the CSI is assumed to be temporally correlated stochastic processes. In terms of signal processing algorithms, there exist various approaches. For example, the MMSE CSI prediction technique is used in [9], Kalman filtering is used in [10, 11] and geodesic-based prediction is used in [12–14]. In [12], the prediction problem is formulated for vector CSI case. The normalised tangent vector of the CSI geodesic and a step size parameter need to be fed back to the transmitter for CSI prediction. The normalised tangent vectors are quantised
with an isotropic Grassmann codebook. In [13], CSI prediction is based on the feedback of the direction and velocity matrix of the CSI geodesic flow. The main contribution of [13] is that a stochastic gradient-based algorithm is proposed for codebook optimisation. In [14], geodesic-based CSI prediction is performed in the frequency domain. The geodesic tangent errors are quantised and fed back to the transmitter for reconstructing the high-resolution CSI. An improved tangent space quantisation technique is proposed using Householder transform and local codebook concept. A tensor-based framework for predicting the MIMO channel is proposed in [15]. In this approach, the channel prediction is performed in a transformed domain, namely on the transformed tensor elements, instead of directly predicting the channel coefficients. In [16], a transmitter side CSI index prediction scheme is proposed. In this scheme, the statistical information about the channel behaviour is collected to build the CSI index transition tables or dictionary first. With this information at hand, the future CSI index can be predicted based on the past CSI indices by look-up-table or dictionary.

In practical MIMO–OFDM systems, clustering feedback (one CSI feedback is done for a cluster of adjacent subcarriers) is usually used for feedback reduction. The performance degradation introduced by clustering can be mitigated by frequency domain CSI interpolation techniques [17, 18]. Three CSI interpolation techniques are discussed in [17] for MIMO–OFDM systems without taking the CSI quantisation into account. The geodesic-based CSI interpolation technique is investigated in [18] where fixed codebook is used for CSI quantisation.

In this paper, an adaptive codebook-based CSI prediction and interpolation scheme is proposed for the multiuser MIMO–OFDM systems with feedback delay and clustering feedback in FDD systems. In the proposed scheme, geodesic-based CSI prediction is performed at the receiver to mitigate the feedback delay effect. Then the predicted CSI is quantised and fed back (clustering feedback) to the transmitter. At the transmitter, geodesic-based CSI interpolation is performed in the frequency domain to mitigate the clustering feedback effect. A unified approach is used for both CSI prediction and interpolation which enables the hardware reuse. Since the preliminary studies show that the performance gain assumed by the CSI prediction and interpolation is limited by the low-resolution CSI quantisation, we developed an adaptive codebook technique to support the proposed CSI prediction and interpolation scheme. The effectiveness of the proposed approach is demonstrated using extensive numerical simulations.

Throughout this paper, (·)−1, (·)T and (·)H denote the matrix inversion, transpose and conjugate transpose, respectively. Ik denotes the k-by-k identity matrix. A scalar is denoted by a boldface italic lowercase character. A matrix is denoted by a boldface italic capital character.

## 2 System formulation

Consider a MU-MIMO–OFDM broadcast system with limited CSI feedback. A base station equipped with Nt transmit antennas will transmit to K (K ≤ Nt) active users each with a single receive antenna (Nr = 1). The received signal on the kth subcarrier of the nth OFDM symbol for the kth user is given by

$$y_k(l, n) = \frac{P}{K} h_k^H(l, n) f_k(l, n) s_k(l, n) + w_k(l, n)$$

(1)

where the subscript k denotes the user index. s_k is the transmitted symbol. y_k is the received signal. f_k is the beamforming vector. h_k^H is the complex row vector of the MISO channel. w_k is the complex Gaussian noise with distribution N(0, σ^2). P is the total transmit power. For simplicity, the subcarrier and OFDM symbol indices l and n will be omitted when there is no ambiguity.

Suppose the power is equally allocated to each user, the signal-to-interference-plus-noise ratio (SINR) at the kth user can be given by [19]

$$\text{SINR}_k = \frac{(P/K) |h_k^T f_k|^2}{\sigma^2 + (P/K) \sum_{i \neq k} |h_i^T f_k|^2}$$

(2)

thus the sum rate R on the considered subcarrier is

$$R\text{(SNR)} = \sum_{k=1}^{K} \log_2 (1 + \text{SINR}_k)$$

(3)

where the signal-to-noise-ratio is defined as SNR = P/σ^2. Suppose zero-forcing (ZF) is used for transmit processing, then the precoder F can be designed based on the quantised channel direction information (CDI) fed back from each user, that is

$$F = H^{D}(HH^{D})^{-1}$$

where $\tilde{h}_k$ denotes the quantised CDI (defined as $\tilde{h}_k = h_k/\|h_k\|_2$) of the kth user. H is the aggregated quantised CDI matrix. Note that $f_k$ is the normalised kth column of F.

In the above formulation, we assume that there is no feedback delay. However, in practice, to mitigate the performance degradation caused by feedback delay and clustering feedback, we proposed an adaptive codebook-based geodesic CSI prediction and interpolation scheme.

The joint CSI prediction and interpolation scheme is shown in Fig. 1. Each user will use the central subcarrier of each subcarrier cluster to perform the T_D-step CSI prediction to mitigate the feedback delay. Then the predicted CSI will be

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**Fig. 1** Principle of the geodesic-based CSI prediction and interpolation

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<table>
<thead>
<tr>
<th>Delayed CSI</th>
<th>Receiver side CSI prediction (Time domain)</th>
<th>Interpolated CSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>t=0</td>
<td>t=1</td>
<td>t=T_D</td>
</tr>
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</table>

- **Cluster 2** is directly observed as the geodesic CSI.
- **Cluster 1** is observed as the predicted CSI (quantised).
- The transmitted CSI is observed as the predicted CSI (interpolated).
expressed as spans the same basis of the subspace. According to (5), the corresponding point on the curved space [20].

Let \( \mathbb{C} \) denote a complex field. Grassmann manifold \( G(n, p) \) with \( p < n \) is a set of \( p \)-dimensional subspaces in \( \mathbb{C}^n \) where a point on the Grassmann manifold is a class of equivalent \( n \)-by-\( p \) semi-unitary matrices [20]. These matrices are equivalent in the sense that the columns of each matrix spans the same \( p \)-dimensional subspace in \( \mathbb{C}^n \). The class of equivalent matrices (a point on the \( G(n, p) \)) can be expressed as

\[
[X] = \{ XU_p, : X \text{ is a } n \times p \text{ semi-unitary matrix, that is, } X^H X = I_p \text{ and } U_p \text{ is any } p \times p \text{ unitary matrix} \}
\]  

where \( [\cdot] \) denotes the equivalent class. \( X \) is one particular basis of the subspace. It can be shown that SINR, defined in (2) will not change with the variations of CSI as long as the CSI subspace for each user is invariant. Thus the CSI (i.e. CDI) in Section 2 is just a special case of the Grassmann manifold with \( n = N_r, \ p = 1 \). In light of this, the CSI prediction and interpolation can be solved using differential geometry tools (such as geodesic) defined on the Grassmann manifold.

3.2 Geodesic-based CSI prediction and interpolation

The basic idea of the geodesic-based CSI prediction (or interpolation) is that the geodesic on the Grassmann manifold can be used as the one-order approximation to the evolving trajectory of the CSI during a short time (or frequency) interval, respectively. Here, the geodesic is defined to be the shortest path between two points on a curved space [20].

We first illustrate the geodesic approach in a general setting where the CSI under consideration is a \( n \)-by-\( p \) semi-unitary matrix. Suppose at the reference time \( 0 \) (or frequency \( 0 \) the CSI is \( X(0) \) where its columns span a subspace. According to (5), the corresponding point on the Grassmann manifold is

\[
[X(0)] = \{ X(0)U_p, : X^H(0)X(0) = I_p, \ U_p \text{ is any } p \times p \text{ unitary matrix} \}
\]

which is a class of equivalent semi-unitary matrices whose columns span the same subspace. \( X(0) \) defines a particular basis of the subspace. For simplicity, we will refer to \( X(0) \) as a point on the Grassmann manifold in the following.

The geodesic curve on the Grassmann manifold starting from \( X(0) \) is given by an exponential flow with one parameter [20]

\[
X(t) = Q(0) \exp(vB(0))I_{n,p}
\]

where \( v \) is the parameter of the curve, \( \exp(\cdot) \) denotes the matrix exponential operator and \( Q(0) \) is an unitary matrix

\[
Q(0) = \begin{pmatrix} X(0) & X^\perp(0) \end{pmatrix}
\]

where \( X(0) \) denotes an orthonormal basis of the orthogonal complement of the subspace spanned by the columns of \( X(0) \). \( B(0) \) is a skew-hermitian matrix of the form

\[
B(0) = \begin{pmatrix} 0 & -A(0) \\ A(0) & 0 \end{pmatrix}, \quad A(0) \in \mathbb{C}^{(n-p) \times p}
\]

\( I_{n,p} \) is the matrix formed by the first \( p \) columns of \( I_n \) and can be expressed as \( I_{n,p} = (I_p \ 0_{(n-p) \times p}) \).

For the geodesic on the Grassmann manifold, \( Q(0) \) characterise the starting point and \( B(0) \) characterises the initial geodesic velocity at time \( 0 \). The geodesic curve can be regarded as being generated by rotating (corresponds to the exponential term) the starting point \( X(0) \) (or equivalently \( Q(0) \)) with constant angular velocity \( B(0) \). Once \( X(0) \) and \( B(0) \) are known, the geodesic is determined. Since the geodesic velocity matrix \( B(0) \) can be determined by any two points on the geodesic, two CSIs completely determine a geodesic.

Thus the key issue is how to determine the geodesic velocity \( B(0) \) given two points \( X(0) \) and \( X(u) \) on the geodesic. Previous research [20–22] has shown that the cosine-sine decomposition (CSD) [23] plays a crucial role in solving this problem. Firstly, assuming \( n > 2p \), perform the CSD on matrix \( Q(0)X(u) \).

\[
Q(0)X(u) = \begin{pmatrix} X^H(0)X(u) & X^H(0)X^\perp(u) \end{pmatrix}
\]

\[
= \begin{pmatrix} U_1 & 0 \\ 0 & U_2 \end{pmatrix} \begin{pmatrix} C \\ S \end{pmatrix} V_1^H
\]

where \( U_1 \) and \( V_1 \) are \( p \)-by-\( p \) unitary matrices and \( U_2 \) is a \( (n-p) \)-by-\( (n-p) \) unitary matrix. \( C \) and \( S \) are defined as

\[
C = \text{diag}(\cos \theta_1, \ldots, \cos \theta_p),
\]

\[
S = \text{diag}(\sin \theta_1, \ldots, \sin \theta_p)
\]

where \( 0 \leq \theta_1 \leq \theta_2 \leq \cdots \leq \theta_p \leq \pi/2 \) is the principal angle between the two subspaces \( [X(0)] \) and \( [X(u)] \) [23]. It can be shown that geodesic velocity-related matrix \( A(0) \) can be determined by

\[
A(0) = \tilde{U}_2 \Theta U_1^H
\]

where \( \tilde{U}_1 \) is defined in (11), \( \tilde{U}_1 \) is the first \( p \) columns of \( U_2 \) defined in (10) and \( \Theta \) is defined as \( \Theta = \text{diag}(\theta_1, \theta_2, \ldots, \theta_p) \). Furthermore, it can be shown that [20]

\[
\exp(B(0)) = URU^H
\]

where \( U = \text{diag}(U_1, U_2) \) is a block diagonal matrix and \( R \) is
defined as

$$R = \begin{pmatrix} C & -S & 0 \\ S & C & 0 \\ 0 & 0 & I_{N-2p} \end{pmatrix}$$  \hspace{1cm} (14)$$

For CSI prediction, the variable \(v\) in (7) is used to represent the normalised time. Choose the second reference point \(u\) in (10) to be the normalised time 1 (i.e. \(u = 1\)). Given the CSI of two time samples \(X(0)\) and \(X(1)\), the key issue is how to predict the CSI at a future discrete time sample at \(t > 1\). From (13), it is easy to show that

$$\exp(tB(0)) = UR^HU^H$$  \hspace{1cm} (15)$$

for an integer \(t > 1\). Thus, the CSI at the normalised time \(v = t\) can be predicted by sampling the geodesic at time \(t\), that is

$$X(t) = Q(0)UR^HU^HI_{np}$$  \hspace{1cm} (16)$$

For CSI interpolation, the variable \(v\) in (7) is used to represent the discrete frequency indices for subcarriers. Choose the second reference point \(u\) in (10) to represent the \(N\)th subcarrier (i.e. \(u = N\)). Given the CSI of two adjacent pilots \(X(0)\) and \(X(N)\), the key issue is how to interpolate the CSI for subcarriers \([X(1)\) through \(X(N-1)\] between the two pilots. As in the CSI prediction case, define a block diagonal matrix \(\hat{R}\) similar to (14)

$$\hat{R} = \begin{pmatrix} \cos(\Phi/N) & -\sin(\Phi/N) & 0 \\ \sin(\Phi/N) & \cos(\Phi/N) & 0 \\ 0 & 0 & I_{N-2p} \end{pmatrix}$$  \hspace{1cm} (17)$$

Here, \(\Phi = \text{diag}(\phi_1, \phi_2, \ldots, \phi_p)\) where \(\cos(\cdot)\) and \(\sin(\cdot)\) only operate on the diagonal elements of the matrix argument. From (16) and (20), the CSI between the two pilots \(X(0)\) and \(X(N)\) can be interpolated by

$$X(f) = Q(0)UR^HU^HI_{np}, \quad \text{for } f = 1, 2, \ldots, N-1$$  \hspace{1cm} (18)$$

### 3.3 Adaptive Codebook Scheme

Our preliminary studies show that the performance gain assumed by CSI prediction and interpolation is limited by the low-resolution CSI quantisation. Hence, based on the adaptive codebook technique in [5], a simplified scheme is proposed to reduce the CSI quantisation error. An adaptive local codebook is constructed for each subband (a group of subcarriers) by rotating and scaling a root codebook (e.g. an isotropic codebook) to provide a better quantisation performance. Codebook rotation operation aligns the codebook centre with the channel statistical direction without changing the distance between the codebook centre and any codeword in the codebook. Codebook scaling operation reduces the distance between the codebook centre and any codeword by a factor \(\alpha(0 < \alpha < 1)\) without changing the codebook centre. In [5], the local codebook centre and radius is determined by the long-term CSI (e.g. channel covariance matrix), which should be known at both the receiver and transmitter. Thus, besides the short-term CSI (codeword index of the precoder or CDI), the long-term CSI also needs to be fed back from the receiver to the transmitter. In this paper, instead of using long-term CSI to determine the local codebook centre, the most recent short-term CSIs (already known at both transmitter and receiver through feedback) are used as the adaptive codebook centres for adaptive codebook construction at the transmitter and receiver. For initialisation purpose, the first short-term CSI feedback could be based on an isotropic codebook (e.g. the root codebook). This CSI feedback will be used as the codebook centre for the adaptive codebook construction at both the receiver and transmitter. The adaptive codebook will be updated periodically, for example, for every \(L\) frames and the choice of \(L\) depends on the channel temporal correlation. Furthermore, fixed scaling factor is used in the current design. Thus a scaled codebook can be constructed beforehand based on the root codebook and only the short-term CSI needs to be fed back. To construct the adaptive codebook, the complexity for codebook scaling (defined in [5]) can be neglected since the scaled codebook can be constructed offline if fixed scaling factor is used. Thus for each update period, only the codebook rotation is needed on each subband. Codebook rotation can be implemented by multiplying each codeword in the scaled codebook by a unitary matrix \((Nt\text{-by-}Nt\text{ in our case})\). The rotation matrix can be constructed based on the original and targeted codebook centre as defined in [5].

### 4 Simulation results

Numerical simulations are based on a multiuser MIMO–OFDM system with the LTE system profile. One base station equipped with four transmit antennas \((N_t = 4)\) transmits data to two users \((K = 2)\) where each user is equipped with a single receive antenna \((N_r = 1)\). A downlink frame consists of 10 subframes. Denote the time duration for each subframe as one transmission time interval (TTI) which is 1 ms. The FFT size of the OFDM system is 1024. The subcarrier spacing is 15 kHz. Six hundred data subcarriers are used in each OFDM symbol. The MIMO channel model used in our simulations is the 3GPP 6-path typical urban (TU) channel without spatial correlation. The vehicular speed is 3 km/h (coherent time \(T_c\) is around 200 TTIs). Channel is invariant in one TTI and varies between subframes according to a pre-specified temporal correlation. In the simulations we assume that each user has perfect CSI estimation.

The following simulations investigate the sum rate performance of the multiuser MIMO–OFDM system for different scenarios. In the figures, ‘subcarrier FB’ denotes per subcarrier feedback whereas ‘cluster FB’ denotes per clustering feedback. ‘Fixed CB’ denotes the 4-bit fixed Householder codebook adopted in LTE. ‘Adapt CB’ denotes the proposed adaptive codebook constructed from the 4-bit LTE codebook.

**Experiment 1:** CSI feedback delay and clustering effect with unquantised/quantised CSI: We first evaluate the sum rate performance of the multiuser MIMO–OFDM system in the presence of feedback delay and clustering. Suppose the feedback delay is \(T_D\) TTIs and the cluster size is \(N\). As can be seen in Fig. 2, feedback delay and clustering cause the sum rate degradation. For quantised CSI case, the sum rate loss due to feedback delay and clustering is not as evident as in the unquantised CSI case. This is because that the low-resolution CSI quantisation dominates the system performances for this experiment setup.

**Experiment 2:** CSI prediction using unquantised CSI: In this experiment, we evaluate the sum rate performance of the...
multiuser MIMO–OFDM system with feedback delay and CSI prediction using unquantised CSI. The simulation results are shown in Fig. 3 where the feedback delays are set to 20 TTIs (0.1T_c) and 40 TTIs (0.2T_c) respectively. As shown in the figure, feedback delay causes significant sum rate loss and the CSI prediction is quite effective in mitigating the sum rate loss due to feedback delay.

Experiment 3: CSI interpolation using unquantised CSI: In this experiment, we evaluate the sum rate performance of the multiuser MIMO–OFDM system with clustering feedback and CSI interpolation using unquantised CSI. The simulation results are shown in Fig. 4. For cluster size N = 6, you can see the sum rate performance improvement provided by the CSI interpolation. However, for cluster size N = 12, the performance improvement provided by the CSI interpolation is negligible since the pilots spacing is approximately equal to the coherent bandwidth (12 subcarriers) and thus the CSI interpolation performance degrades.

Experiment 4: Adaptive codebook-based CSI quantisation: In this simulation, we evaluate the sum rate performance of the multiuser MIMO–OFDM system with the proposed adaptive codebook scheme. Each adaptive codebook will be constructed from the 4-bit fixed LTE Householder codebook and will be used for a cluster of subcarriers (cluster size = N). The adaptive codebook will be updated every L TTIs. The scaling factor for the adaptive codebook construction is fixed and set to be 0.5. The sum rate performances for the fixed and adaptive codebook cases are shown in Fig. 5. It can be seen that the adaptive codebook scheme can improve the sum rate performance due to its reduced quantisation error. Improved performance can be
achieved by reducing the cluster size and/or the updating interval.

**Experiment 5: CSI prediction using quantised CSI (with fixed and adaptive codebooks):** In Fig. 6, we evaluate the sum rate performance of the system with feedback delay, CSI prediction and adaptive codebook. In this simulation, per subcarrier feedback is used and the feedback delay is set to 20 TTIs (0.1T_s). The sum rate for fixed codebook quantisation without feedback delay is plotted as a reference (black solid line). The sum rate loss due to feedback delay (line with mark ‘▼’) can be seen by comparing it with the reference. By applying the CSI prediction with fixed codebook quantisation (line with mark ‘○’), the delay effect can be almost eliminated. If the adaptive codebook is used even without CSI prediction (line with mark ‘◇’), the performance is better than that of the case without delay (but using the fixed codebook quantisation). The sum rate performance will be improved significantly if both CSI prediction and adaptive codebook are applied (line with mark ‘□’). In this simulation, one adaptive codebook is constructed for 12 adjacent subcarriers with scaling factor 0.5 and is updated every 5 TTIs.

**Experiment 6: CSI interpolation using quantised CSI (with fixed and adaptive codebooks):** In Fig. 7, we evaluate the sum rate performance of the system with clustering feedback, CSI interpolation and quantised CSI. The cluster size N = 12 and suppose there is no feedback delay. The sum rate for subcarrier feedback delay and fixed codebook quantisation is plotted as a reference (black solid line). The sum rate loss due to the clustering feedback (line with mark ‘□’) can be seen by comparing it with the reference. By applying the CSI interpolation with fixed codebook quantisation (line with mark ‘○’), the clustering feedback effect can be mitigated to some extent. If the adaptive codebook is used even without CSI interpolation (line with mark ‘◇’), the sum rate performance can be improved significantly compared to that in the fixed codebook quantisation and subcarrier feedback case. The sum rate performance will be improved further if both CSI interpolation and adaptive codebook are applied (line with mark ‘▼’). In this simulation, one adaptive codebook is constructed for 12 adjacent subcarriers with scaling factor 0.5 and will be updated every 5 TTIs.

**Experiment 7: Mitigate the CSI feedback delay and clustering by joint CSI prediction and interpolation:** In the following simulations, we investigate the sum rate performance of the system with CSI prediction and interpolation in the presence of both feedback delay and clustering feedback using quantised CSI (with both fixed and adaptive codebooks).

In Fig. 8a, the feedback delay T_D = 20 TTIs (0.1T_s) and cluster size N = 12. As mentioned before, quantisation error, feedback delay and clustering feedback are the three performance degrading factors. Used as references are sum rate performances for the following three cases: only with the fixed CB quantisation (black solid line), only with feedback delay (blue dashed-dotted line) and only with clustering FB (black dashed line). Among the three references, we can see that quantisation error is the dominating factor here. The sum rate loss due to feedback delay and clustering (line with ‘□’) with fixed CB quantisation is large. If the joint CSI prediction and interpolation scheme are applied with fixed CB quantisation (line with ‘×’), the performance loss can be mitigated to some extents. However, the performance improvement is limited since the quantisation error dominates the performance. If the adaptive CB is used, even though only CSI prediction (line with ‘○’) or interpolation (line with ‘◇’) is applied, the sum rate performance is better than the reference with only fixed CB quantisation. Joint CSI prediction and interpolation with adaptive CB (line with ‘△’) provides the best performance. In this simulation, one adaptive codebook is constructed for each cluster with scaling factor 0.5 and will be updated every 5 TTIs.

In Fig. 8b, we increase the feedback delay to T_D = 40 TTIs while keeping other parameters the same as in Fig. 8a. We can still observe the significant performance gain introduced by the joint CSI prediction and interpolation scheme with adaptive CB (line with ‘△’). It is remarkable that, since in this simulation feedback delay is the dominant factor, only applying CSI interpolation is not enough (line with ‘◇’). But only applying CSI prediction with adaptive CB (line with ‘○’) can achieve a pretty good performance gain.

![Fig. 6 Sum rate performance of the multiuser MIMO–OFDM system with CSI prediction and adaptive codebook](image)

![Fig. 7 Sum rate performance of the multiuser MIMO–OFDM system with CSI interpolation using adaptive codebook](image)
In Fig. 8c, we increase the cluster size to \( N = 24 \) while keeping other parameters the same as in Fig. 8a. We can still observe the significant performance gain introduced by the joint CSI prediction and interpolation scheme with adaptive CB (line with ‘\( \Delta \)’). It is remarkable that in this simulation only applying CSI prediction with adaptive CB (line with ‘\( \circ \)’) is good enough. Note that the sum rate performance for joint CSI prediction and interpolation scheme (line with ‘\( \Delta \)’) and that for only the CSI prediction scheme (line with ‘\( \circ \)’) overlap. The CSI interpolation does not provide further performance gain since the pilot spacing is wider than the coherent bandwidth (12 subcarriers) and consequently the CSI interpolation is not effective.

5 Conclusion

In this paper, an adaptive codebook-based CSI prediction and interpolation scheme is proposed for multiuser MIMO–OFDM systems with feedback delay and clustering feedback. In this scheme, geodesic-based CSI prediction is first performed at the receiver to mitigate the feedback delay. The predicted CSI is then quantised and fed back (clustering feedback) to the transmitter. At the transmitter, geodesic-based CSI interpolation is performed in the frequency domain to mitigate the clustering feedback effect. A unified approach is used for both CSI prediction and interpolation which enables the hardware reuse. Since the performance gain assumed by the CSI prediction and interpolation is limited by the low-resolution CSI quantisation, an adaptive codebook technique is proposed to be used to support the CSI prediction and interpolation scheme. To construct the adaptive codebook, only the past short-term CSI (codeword index of the precoder or CDI) feedback is needed. Thus the feedback framework of the proposed scheme can be kept unchanged compared to a system using fixed codebook. Simulation results show that the proposed scheme can effectively mitigate the feedback delay and clustering even with a 4-bit adaptive codebook. Thus the proposed technique is very promising for future MIMO–OFDM communication systems (e.g. LTE-Advanced or 802.16m) where CSI feedback delay and clustering are critical and need to be treated in advanced MIMO technique design.

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Fig. 8 Sum rate performance of the multiuser MIMO–OFDM system with CSI prediction and interpolation using adaptive codebook

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Q1  IET style for matrices and vectors is to use bold italics. Please check that we have identified all instances correctly.

Q2  As per style, all figures are grey scale. But same colour informations mentioned in text. Please rephrase the text accordingly.

Q3  Please provide all author names in Refs. [3, 5, 10, 11, 17, 21].