Low Complexity Beam Selection Scheme Based on Estimated CSI

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Abstract. The beam selection technology based on the discrete lens array (DLA) can greatly reduce the number of RF chains required by mmWave massive multiple-input multiple-out (MIMO) system. However, the performance of the existing beam selection schemes is on the premise of perfect channel state information (CSI). While in practical situation, accurate channel state information must be obtained by the base station before beam selection. In this paper, the channel estimation scheme based on support detection (SD) is used to estimate the state information of large-scale channel by utilizing the structural characteristics of beamspace. Then on the basis of group-iteration (GI) algorithm, we propose the group-iteration beam selection scheme based on estimated CSI. The simulation results show that this scheme can achieve the performance close to beam selection scheme based on perfect CSI, and compared with the traditional beam selection schemes, the proposed scheme also shows performance advantages.

1. Introduction
Millimeter-wave (mmWave) communication, operating in the spectrum of 30-300 GHz, is gradually becoming a key technology for the future 5G communication [1]. Due to the millimeter-scale wavelength (1mm-10mm) and higher spectrum efficiency, it can significantly improve the data transmission rate, provide rich spectrum resources and well support high-dimensional MIMO systems [2], [3].

However, it is difficult to realize mmWave massive MIMO system in practical application. Since each antenna element in MIMO system is usually equipped with a dedicated RF chain [4], it means that large-scale antenna array needs to be equipped with a large number of RF chains, which leads to the unbearable hardware cost. In addition, it has been proved that the energy consumption of RF chain at mmWave frequency is much higher than that at sub-6 GHz frequencies. Moreover, studies have also shown that large-scale antenna arrays in MIMO systems are particularly vulnerable to RF chain defects [5], resulting in additional performance losses.

Therefore, the research on new technologies to reduce the number of RF chains required by MIMO systems is a key challenge to develop mmWave communication more effectively. Beam selection technology based on beamspace MIMO [5] can reduce the number of RF chains required in mmWave massive MIMO systems, and the performance loss can be ignored. By employing a perfectly designed DLA, the conventional spatial channel can be transformed into the beamspace channel [5], such DLA behaves as a convex lens dispersing the signal to all directions of the whole space [6]. We know that each beam requires one single RF chain in beamspace MIMO (B-MIMO) system, therefore, the beam selection technology can reduce the number of RF chains by reasonably selecting a small number of
beams.

The beam selection scheme based on the criterion of magnitude maximization (MM-S) proposed in [7] is simple to implement and also enjoys quite low computational complexity. However, different users are likely to select the same beam, resulting in interference between multiple users. The interference-aware (IA) beam selection scheme proposed in [4] shows higher sum rate than MM-S scheme, but it faces the problem of high computational complexity. In addition, the existing beam selection schemes do not consider the channel state deviation between the perfect CSI and the estimated CSI, which may lead to some errors in the performance.

To overcome the above issue, the group-iteration (GI) beam selection scheme based on estimated CSI is proposed in this paper. First of all, the channel state information is obtained by estimating the beamspace channel based on the SD scheme. Then, on the basis of the original GI algorithm, the information obtained from channel estimation is fused into the beam selection algorithm, and the near optimal beam set is selected with low computational complexity. The multi-user interference is fully considered and the system performance error caused by the deviation of channel state information is minimized. The simulation results show that the proposed scheme can achieve the performance very close to the beam selection scheme based on perfect CSI, and it also shows performance advantages compared with the traditional beam selection scheme.

2. System Model
A typical time-division-duplexing (TDD) mmWave massive MIMO system is considered here, where the base station is equipped with $N$ elements and $N_{RF}$ RF chains. And there are $K$ single-antenna users in the system being served simultaneously. As shown in figure 1, the conventional spatial channel can be transformed into the beamspace channel by employing one carefully designed DLA.

By equipping one dielectric lens in front of the electromagnetic radiator, the lens antenna can gather the electromagnetic radiation into one narrow beam. According to the theory of geometrical optics, the incident signals of different angles can be focused on different receiving antenna subsets in the lens array at the receiving end. Therefore, the transmitting lens array can also separate the leaving signals from different transmitting antenna subsets sufficiently, which is similar to a convex lens, and disperses the signals to all directions of the whole space. Such DLA can be regarded as an $N \times N$ spatial discrete Fourier transform matrix. By calculating the steering vectors of $N$ orthogonal directions $u(\psi_n), n = 1, 2, ..., N$, the matrix can be defined as

$$U = [u(\psi_1^*), u(\psi_2^*), ..., u(\psi_N^*)]^T,$$

where $u(\psi) = 1/[\sqrt{N} \times \exp(-j2\pi\psi n)]_{\text{circ}(N)}$ is the array steering vector, $\psi_n^* = (1/N) \times [n - (N + 1)/2]$ denotes the fixed spatial direction, and the $N$ orthogonal directions cover the entire space area.

![Figure 1. Beamspace MIMO system model.](image)
In the B-MIMO system, the downlink receiver signal vector \( \mathbf{y} = [y_1, y_2, \ldots, y_K]^T \) can be expressed as follows:

\[
\mathbf{y} = \mathbf{H}^H \mathbf{U}^H \mathbf{G} \mathbf{x} + \mathbf{n} = \mathbf{H}_b^H \mathbf{G} \mathbf{x} + \mathbf{n},
\]

where \( \mathbf{x} \) is the original signal vector of size \( K \times 1 \), \( \mathbf{n} \) denotes the additive white Gaussian noise (AWGN) vector considered to be independent and identically distributed (IID) with \( \mathbf{n} \sim \mathcal{CN}(0, \sigma_n^2 \mathbf{E}_K) \). \( \mathbf{G} \) is the precoding matrix in order to alleviate the multi-user interference [7] given by

\[
\mathbf{G} = \alpha \mathbf{F} = \alpha [f_1, f_2, \ldots, f_k], \alpha = \frac{\rho}{\sqrt{\text{tr}(\mathbf{F}^H \mathbf{F})}},
\]

where \( \rho \) is the total transmit power, which is equal to the transmit SNR for \( \sigma_n^2 = 1 \). Here we adopt the Wiener filter (WF) precoders [8] where \( \mathbf{F} \) in (3) is expressed as follows:

\[
\mathbf{F} = \mathbf{F}_{\text{WF}} = (\mathbf{HH}^H + \zeta \mathbf{E})^{-1} \mathbf{H}, \quad \zeta = \frac{\sigma_n^2 K}{\rho}.
\]

In (2), \( \mathbf{h}_k = \mathbf{U}^H \mathbf{h}_k = [\mathbf{h}_{1,k}, \mathbf{h}_{2,k}, \ldots, \mathbf{h}_{K,k}] \) is the beamspace channel matrix of size \( N \times K \), \( \mathbf{h}_{b,k} = \mathbf{U}_k (k = 1, 2, \ldots, K) \) is the corresponding beamspace channel vector of the \( k \)th user containing \( N \) orthogonal beams with spatial angles of \( \psi_1^k, \psi_2^k, \ldots, \psi_N^k \), which can be calculated by the following formula:

\[
\mathbf{h}_{b,k} = \mathbf{U}_k = \sum_{l=0}^{L} \beta_{k}^{(l)} \mathbf{u}(\psi_{k}^{(l)}) = \sum_{l=0}^{L} \mathbf{u}_{c_{k,l}},
\]

where the number of channel propagation paths is \( L + 1 \), \( \mathbf{u}_{c_{k,l}} = \beta_{k}^{(0)} \mathbf{u}(\psi_{k}^{(0)}) \) is the LOS path component of the channel vector, \( \mathbf{c}_{k,l} = \beta_{k}^{(l)} \mathbf{u}(\psi_{k}^{(l)}) (1 \leq l \leq L) \) denotes the \( l \)th NLOS path component, \( L \) is the number of the NLOS path components. For the communication with the \( k \)th user in the path \( l \), \( \beta_{k}^{(l)} \) denotes the complex gain and \( \psi_{k}^{(l)} \) presents the spatial direction. In the mmWave scattering environment, we know that the number of the dominating scatterers is limited. Therefore, the number of the propagation paths \( L \) is much smaller than \( N \), which signifies quite sparse structure in the beamspace channel [5]. This allows us to select small number of beams (i.e., the dominant elements of \( \mathbf{h}_{b,k} \)) to reduce the required numbers of RF chains with negligible performance loss. After beam selection procedure, the system model can be re-expressed as follows:

\[
\mathbf{y}_b \approx \mathbf{H}_b^H \mathbf{G} \mathbf{x} + \mathbf{n}, \mathbf{H}_b = \mathbf{H}_b (\mathbf{s} : \beta_{b,k}),
\]

where \( \mathcal{B} \) denotes the set of the selected beam subscripts for the \( K \) users. We assume that the number of RF chains after beam selection satisfies \( N_{RF} = K \), i.e., each user will be allocated one beam. Here \( \mathbf{H}_b \) is the beamspace channel matrix after beam selection of size \( K \times K \), and the matrix \( \mathbf{\hat{G}} \) of size \( K \times K \) denotes the dimension-reduced precoding matrix.

3. Beam Selection Based On Estimated CSI

As we have discussed in section 1, it is difficult to consider both system performance and computational complexity in MM-S scheme and IA scheme, and the system performance is under the assumption of perfect CSI without considering the channel state bias caused by channel estimation. Therefore, the GI beam selection scheme based on CSI estimation is proposed in this paper, which selects the near optimal beam set with low computational complexity, and integrates the information.
obtained from channel estimation into the beam selection algorithm to minimize the system performance error caused by the deviation of channel state information.

3.1. GI Algorithm
The idea of GI algorithm is to divide all users into two sets according to whether users share the same beam with other users, the fixed users and the iterated users, denoted by \( \mathcal{U}_f \) and \( \mathcal{U}_i \) respectively. For different user sets, different beam allocation methods will be adopted.

1) The user \( k \) will be defined as \( k \in \mathcal{U}_f \) only when the maximum gain beam \( b_k^* \) for the kth user satisfies \( b_k^* \notin \{b_1^*, b_2^*, ..., b_K^*\} \). Take figure 2 (a) as the example, where \( b_1^* = 2, b_2^* = 4, b_3^* = 7 \). Then it can be defined that the fixed users set \( \mathcal{U}_f = \{1,3\} \), since \( b_1^* \notin \{b_1^*, b_2^*, b_3^*\} \) and \( b_3^* \notin \{b_1^*, b_2^*, b_3^*\} \). For users in \( \mathcal{U}_f \), the maximum gain beam can be allocated directly because the beam carries the main power and is not affected by any other users.

2) If the maximum gain beam for the user \( k \) satisfies \( b_k^* = b_i^*, \exists i \in \{1,...,k-1,k+1,...,K\} \), we define that the user \( k \) belongs to the set \( \mathcal{U}_i \). Consider the example shown in figure 2 (a), we can observe obviously that \( \mathcal{U}_i = \{2,4\} \), since \( b_2^* \in \{b_1^*, b_2^*, b_3^*\} \) and \( b_4^* \in \{b_1^*, b_2^*, b_3^*\} \). For the user \( k \in \mathcal{U}_i \), we will employ the iteration algorithm to select the most appropriate beam from the remaining beam set \( \mathcal{N} = \mathcal{N} \setminus \{b_i^* \mid f \in \mathcal{U}_f\} \) as shown in figure 2 (b).

3.2. SD Channel Estimation Scheme
In the uplink of TDD system, it is assumed that the beam space channel remains unchanged during the channel coherence time \( T \). In order to estimate the beamspace channel, all users need to transmit the known pilot sequence to the base station. In the transmission process, the coherent time \( T \) is divided into \( R \) time slices, and each time slice is composed of \( K \) time slot blocks, i.e., \( T = RK \). In each time slice, \( K \) users transmit \( K \) orthogonal pilot sequences through \( K \) slots. For each time slice, during the pilot transmission, the base station uses one combiner \( W_r \) of size \( K \times N \) to merge and receive uplink signals. After pilot transmission is completed in \( R \) time slices, the measurement vector \( z_i \) of size \( T \times 1 \) can be obtained:
where $\tilde{n}_k$ is the uplink equivalent noise, which satisfies the complex Gaussian distribution with mean value of 0 and variance of $\sigma_{UL}^2$. The energy of the uplink pilot sequence is normalized to 1, and the uplink SNR is $1/\sigma_{UL}^2$. Our task is to reconstruct $\hat{h}_k$ reliably based on $\tilde{z}_k$ to obtain the complete beamspace channel $H_u$.

In the beamspace system, the most important energy of the $l$th component $\tilde{c}_{k,l}=Uc_{k,l}$ is concentrated on a few dominant $V$ elements (suppose $V$ is odd for the convenience of discussion), thus $\tilde{c}_{k,l}$ can be considered as a sparse vector [8]. If the position of the strongest element $n^*_l$ in $\tilde{c}_{k,l}$ is determined, we can determine the location of the remaining $(V-1)$ dominant elements with the main energy:

$$\sup(\tilde{c}_{k,l}) = \text{mod}(n^*_l - \frac{V-1}{2}, \ldots, n^*_l + \frac{V-1}{2}).$$

(8)

The main idea of SD algorithm is to decompose the whole channel estimation problem into several sub problems, in which only one channel component is analyzed [9]. After each channel component is processed, the influence of the channel component is eliminated from the total estimation problem. The support set is determined by the position of the strongest element. The channel state information can be obtained more accurately by using the support set, and the influence of error propagation can be reduced.

### 3.3. GI Beam Selection Based on Estimated CSI

Based on the discussion above, we note the GI beam selection scheme mentioned above, the existing MM-S scheme and IA scheme are all based on the assumption of perfect CSI. Considering the channel state deviation between estimated CSI and perfect CSI in practical applications, we propose GI beam selection scheme based on estimated CSI.

Based on the beamspace channel estimation matrix $H^{est} = [\tilde{h}_1, \tilde{h}_2, \ldots, \tilde{h}_K]$ obtained in the previous section, the channel gain matrix can be constructed by calculating the absolute square values of $N \times K$ elements in $H^{est}$, denoted by $H^{est} \in \mathbb{H}^{N \times K}$. The $k$th column in $H^{est}$, denoted by $h^{est}_{\cdot,k} = [h^{est}_{1,k}, h^{est}_{2,k}, \ldots, h^{est}_{N,k}]^T (k = 1, 2, \ldots, K)$, represents the beamspace channel estimation gain vector of the $k$th user. We sort the $N$ elements in $h_{\cdot,k}^{est}$ (i.e., the gain of $N$ beams corresponding to the $k$th user) in descending order, and select the beam number with the maximum gain value, which is marked by $b_k^*$ as mentioned in previous part, note that $b_k^* \in \mathcal{N} = \{1, 2, \ldots, N\}$.

In the previous part, we have described how to divide all users into two groups. In this part, we mainly introduce how to select suitable beam for the iterated users $\mathcal{U}_i$. The specific selection scheme is shown in Algorithm 1.

For the iterated users, we know that each user shares the same maximum gain beam with at least one other user. In Algorithm 1, on the basis of the original iteration algorithm, we integrate the strongest element detection algorithm of channel estimation into the beam allocation algorithm to reduce the system performance error caused by the deviation of channel state information. In each iteration process, we will repeat the iterative part of algorithm 1 to allocate the most reasonable beam for one user in the set $\mathcal{U}_i$ until all users in the set $\mathcal{U}_i$ have been allocated one unshared beam.
After beam selection for fixed users and iterative users, the selected beam set can be expressed as follows:

\[ B = \{ b_f^+ | f \in \mathcal{U}_f \} \cup \{ b_i^+ | i \in \mathcal{U}_i \} \]  \hspace{1cm} (9)

**Algorithm 1** Iteration Algorithm Based on Estimated CSI

**Input:** \( \hat{\mathbf{H}}_{g}, \mathcal{U}_i, \mathbf{\tilde{z}}_k, \mathbf{W} \)

**Initialization:** \( \mathcal{N} = \{1,2,\ldots,N\} \setminus \{b_f^+ | f \in \mathcal{U}_f\} \), \( B_i = \emptyset \)

**ITER:**

for \( k \in \mathcal{U}_i \)

\[ b_k^+ = \arg \max_{n_k \in \mathcal{N}} \{ h_{g,n_k} \} \]

end for

for \( k \in \mathcal{U}_i \)

1. \( k_{\text{curr}} = \arg \max_{k_{\text{curr}} \in \mathcal{N}} \{ h_{g,k_{\text{curr}}} + \mathbf{W} h_{k_{\text{curr}}}^H \mathbf{\tilde{z}}_{k_{\text{curr}}} \} \),

2. Allocate the beam \( b_k^+ \) to user \( k_{\text{curr}} \),

3. \( \mathcal{U}_i = \mathcal{U}_i \setminus \{k_{\text{curr}}\} \) and \( \mathcal{N} = \mathcal{N} \setminus \{b_k^+\} \),

4. \( B_i = B_i \cup \{b_k^+\} \).

end for

if \( \mathcal{U}_i = \emptyset \) then

Repeat ITER

else

Stop

end if

**Output:** \( B_i \)

4. System Simulation Results

In this section, we present the simulation results to illustrate the system performance of the proposed GI beam selection scheme based on estimated CSI. We consider one typical mmWave massive MIMO system with parameters as: \( N = 256, K = 32 \), in which every user has a single receiving antenna. For the channel model of the \( k \text{-th} \) user, we assume the total number of the propagation paths \( L = 3 \), having one LOS component with \( \beta_k^{(1)} \sim \mathcal{CN}(0,1) \) and two NLOS components with \( \beta_k^{(i)} \sim \mathcal{CN}(0,10^{-1})(i = 2,3) \), and the spatial direction \( \psi_k^{(i)} \) follows the uniform distribution independent of each other with in \([-1/2,1/2]\).

4.1. Sum Capacity Performance Analysis

Figure 3 contains the sum capacity performance of original GI scheme under perfect CSI and proposed GI scheme based on estimated CSI. Meanwhile, the sum capacity of MM-S scheme and IA scheme under perfect CSI and estimated SCI are listed for comparison. The sum capacity can be calculated according to the following formula [7]:

\[
C = \sum_{i=1}^{K} \log_2 \left( 1 + \rho \frac{\| \alpha \|^2}{K} \left| \mathbf{h}_k^H \mathbf{f}_i \right|^2 \right) \left( \rho \frac{\| \alpha \|^2}{K} \sum_{m \neq k} \left| \mathbf{h}_{m}^H \mathbf{f}_i \right|^2 + \sigma^2 \right)^{-1},
\]  \hspace{1cm} (10)

where \( \rho, \mathbf{f}_i, \sigma^2 \) and \( \alpha \) are mentioned in (3) and (4), and \( \mathbf{h}_k \) denotes the channel vector of the \( k \text{-th} \) user.
As shown in Figure 3, we find that the GI scheme performs better than the traditional MM-S scheme under both perfect CSI and estimated CSI, especially at high SNR. We know that MM-S scheme suffers high probability that multiple users share the same beam, and the multiuser interference will result in non-negligible performance loss. Moreover, the performance of MM-S scheme under estimated CSI is much worse than that under perfect CSI, since the performance error caused by channel state information deviation is not considered. In contrast, on the basis of original GI algorithm, the proposed GI scheme based on SD channel estimation integrates the algorithm for detecting the strongest elements of channel estimation into the beam allocation algorithm. Therefore, the performance under CSI estimation is very close to that under perfect CSI. In addition, we can observe from Figure 3 that the performance of IA beam selection scheme is slightly better than that of GI beam selection scheme under perfect CSI, but the performance under estimated CSI is much worse than that under perfect CSI as same as MM-S scheme. We can also intuitively find that the performance of proposed scheme is better than that of IA scheme under estimated CSI.

4.2. Complexity Analysis

In this part, we will compare the complexity of the proposed GI beam selection scheme based on SD channel estimation with the existing MM-S scheme and IA scheme, which is shown in Table 1.

Table 1. Complexity comparison of beam selection schemes

| Beam Selection Scheme | MM-S | IA | SD-based GI |
|-----------------------|------|----|-------------|
| complexity            | $\mathcal{O}(1)$ | $\mathcal{O}(K_i^2)$ | $\mathcal{O}(K_i)$ |

The implementation of MM-S scheme is simple. It only extracts the maximum gain beam while constructing the channel gain matrix, thus its complexity is $\mathcal{O}(1)$. For IA scheme, its complexity mainly comes from the process of selecting beams for interference users. If there are $K_i$ interference users in total $K$ users, then when selecting the beam for the user $k$ ($k=1,2,...,K_i$), the number of beams to be compared is $N-(K-K_i)-(k-1)$. Through the sum of the arithmetic sequence, the number of comparisons will be $0.5K_i^2 + K_i(N-K+0.5)$, thus the complexity is $\mathcal{O}(K_i^2)$. The complexity of the
proposed algorithm mainly comes from the process of selecting beams for iteration users. As shown in Algorithm 1, each iteration process only needs to compare the current user with the users sharing the same beam, thus the complexity is \( \mathcal{O}(K_I) \). It is obvious that the complexity of the algorithm proposed in this paper is lower than that of the IA scheme, especially when \( K_I \) is close to \( K \).

5. Conclusion

On the basis of the group iteration algorithm, the estimated CSI based GI beam selection scheme is proposed in this paper. From the simulation results, we can see that the proposed algorithm has certain performance advantages in terms of sum capacity. Especially, the performance under estimated CSI is not only quite close to the system performance under perfect CSI, but also better than the existing MMS scheme and IA scheme. In addition, through the analysis of the complexity, we can observe that the proposed algorithm also enjoys great comprehensive advantage in the trade-off between system performance and complexity.

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