Joint User Scheduling and Beam Selection for Maritime Large-scale Antenna Systems

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Abstract: Since the overall distribution of users in the sea area is sparse, it will appear densely in a local angle domain. Specifically, the 3D massive MIMO antenna system are established, which are with the ability to distinguish users in the same horizontal direction as well as vertical direction. According to this, a joint user scheduling and beam selection scheme based on the automatic identification system (AIS) is proposed to solve the problems that of the interference cancellation for the users in the angle domain. In particular, the proposed scheme divides the beam according to the users’ location information. Furthermore, we select the user with the highest priority in the beam to form a set of the users in serving, in the meanwhile, the greedy algorithm is used to schedule the user combination to achieve the greatest sum rate. By means of the numerical results, it is shown that the proposed scheme can be used to schedule and serve users in the case of crowded angle domain, and the scheme can obtain near-optimal sum rate.

1. Introduction

The settlement of maritime disputes, marine disaster forecasting, oceanic mineral exploration and protection of sea lanes security are main challenge of “Marine Silk Road ” with the strategy of “one belt and one road” . Marine wireless communication provides technical support for this challenge. At present, satellite communication is the main means of marine communication. The satellite has the characteristics of wide frequency band and extensive coverage, but its life span is short, communication price is expensive and the communication quality are affected by bad weather are obvious, especially when maritime disputes occur, data delay and security issues will be more prominent. In order to solve the above shortcomings of satellite communications in the maritime areas. We consider a massive multiple-input multiple-output (MIMO) base station (BS) with analog beamforming. The analog beamforming has only one RF chain connected to all antenna elements. It only supports single-stream transmission and its communication rate is low, but its implementation is simple and power consumption is small. For the characteristics of sparse distribution of maritime users and low speed, it is economically feasible to use analog beamforming. And compared to digital beamforming, analog beamforming compensates for the deficiencies by reducing hardware costs. Many extensive research efforts have been devoted to analog beamforming relies on RF circuits that can be controlled to modify the phase of an incoming signal by a limited number of distinct phases [1][2].

The reason why massive MIMO with analog beamforming has gained more and more attention is because it not only reduces system overhead but also improves spectral efficiency and energy efficiency within limited time-frequency resources, and massive MIMO has also become one of the
key technologies of the fifth generation mobile communication system. However, the current communication field still remains on the classical uniform linear array (ULA), and its research method is not suitable for an uniform planar array (UPA) with vertical resolution because it does not involve the vertical degree of freedom [3]. Therefore, it is necessary to conduct in-depth research on practical 3-dimensional massive MIMO. As we well known, using large-scale antennas in the vertical and horizontal directions, signals in different directions can be concentrated on a limited antenna, which greatly creates additional degrees of freedom to avoid inter-beam interference, while also increasing the sum rate [4], because of the sparsity of maritime users, the feature of massive MIMO has been further enhanced.

In the traditional user scheduling schemes [5], in order to maximize the system’s sum rate, it is necessary to obtain accurate channel state information (CSI) for each user in the system, and the system’s overhead is bound to be large. In the maritime scene, the overall distribution of users is sparse, and the local angle domain may be dense. A joint user scheduling and beam selection scheme based on automatic identification system (AIS) is proposed to solve this problem. And we have noticed that compared to users on land, maritime users have the following significant features: one is that ships on the sea follow specific shipping lanes, the other is that each ship is equipped with Automatic Identification System (AIS), which can provide location information. In the proposed scheme, first, a special antenna array [6] is used to transform the spatial domain into the beam domain, which is mathematically equivalent to a spatial discrete Fourier transform (DFT), and its beam can evenly divide the entire 3D space, then, using the AIS location information to mine the correspondence between the beam and the user’s location, the user’s location information can be used to determine the served beam, and finally the highest priority candidate set is scheduled in each beam, according to the sum rate. We use the greedy algorithm to select the user set of services according to the weighted sum rate maximum criterion. Compared with the traditional scheme, the proposed scheme only needs to acquire the channel state information of the scheduled users, which greatly reduces the computational complexity and reduces the system overhead.

2. System model

For simplicity of illustration, let us consider the offshore communication scenario composed of a base station (BS) with $N$ transmit antennas as well as $N_{RF}$ RF chains serving $K$ single antenna users (see Figure 1). The users are assumed to be randomly located inside a ring away from the BS to model the scenario with high channel correlation. In this 3-dimensional (3D) massive MIMO system, in order to avoid intra-beam interference, one beam can only support one user. [4].

In the 3D massive MIMO, the received signal vector $y$ of dimension $K \times 1$ for all $K$ users can be denoted by

$$y = H^{K \times WPs} + v,$$  

(1)
where $H=[h_1, h_2, \cdots, h_K]$ is the channel matrix with the dimension of $N \times K$, $h_i \in \mathbb{C}^{N \times 1}$ is the $k^a$ column of the matrix $H$ which represents the channel vector between the $k^a$ user and the BS. $W=[w_1, w_2, \cdots, w_K]$ is the precoding matrix with the dimension of $K \times K$, $w_k \in \mathbb{C}^{N \times 1}$ is the $k^a$ column of the matrix $W$ with $\|w_k\|=1$ for $k=1,2,\cdots, K$, $P=\text{diag}\{p\}$ is the total transmitted power by the BS, and each user is assigned same power according to the previous assumption. $s \in \mathbb{C}^{K \times 1}$ is the signal vector for all $K$ single antenna users with $E\{ss^H\}=I_K$, $\psi \in \mathbb{C}^{N \times 1}$ is additive white Gaussian noise vector following the distribution $CN(0, \sigma^2 I_N)$. In this paper, the channel vector of the $k^a$ user can be modelled as [7]

$$h_k = \frac{1}{\sqrt{LD^h_k}} \sum_{l=1}^{L} \alpha_{1,l} a(\phi_{1,l}, \Theta_{1,l}),$$

(2)

where $D_l$ represents the distance between the $k^a$ user and the BS, $\alpha_{1,l}$ denotes small-scale fading parameters of the $k^a$ user on the $l^{th}$ path, $\beta$ denotes path loss exponent, $L$ denotes the number of rays. Then, we consider a 3-ray channel model which means $L=3$, where $a_{1,1} a(\phi_{1,1}, \Theta_{1,1})$ is the LoS component of $h_k$ and $a_{2,3,l} a(\phi_{2,3,l}, \Theta_{2,3,l})$ is the NLoS component of $h_k$, and $a(\phi, \theta)$ is the array steering vector of 2-dimension. For an $N=N_1 \times N_2$ uniform planar array (UPA), $N_1$ and $N_2$ are the number of antennas in the horizontal and vertical directions, respectively, $a(\phi, \theta)$ can be denoted by [8]

$$a(\phi, \theta) = a_{\psi_1}(\phi) \otimes a_{\psi_2}(\theta),$$

(3)

where $a_{\psi_1}(\phi) = \frac{1}{\sqrt{N_1}}[e^{j2\pi \psi_1 \phi}]$ for $i \in \mathbb{T}(N_1)$, $a_{\psi_2}(\theta) = \frac{1}{\sqrt{N_2}}[e^{j2\pi \psi_2 \theta}]$ for $j \in \mathbb{T}(N_2)$, among them $\mathbb{T}(t) = \{p-(t-1)/2, t=0,1,2,\cdots, p-1\} \cdot \phi \pm \frac{d_1}{\lambda} \sin \theta$ and $\theta \pm \frac{d_2}{\lambda} \sin \bar{\theta}$ denote the spatial azimuth and elevation, respectively, where $\bar{\theta}$ and $\bar{\theta}$ are the physical direction of azimuth and elevation, respectively. As mentioned before, in the case of the sea, each ship has a fixed shipping lanes, $\bar{\theta}$ is the physical direction of the elevation satisfied $0 < \bar{\theta} < \pi/2$. $\lambda$ is the carrier wavelength. $d_1 = d_2 = \frac{\lambda}{2}$ are the spacing of antenna in horizontal and vertical, respectively.

In the proposed scheme, a special antenna array [8] which function is similar to a lens antenna has been used to transform the spatial domain into beam domain. Specifically, such UPA plays the role of matrix $U \in \mathbb{C}^{N \times NN}$ which is mathematically equivalent to a discrete Fourier transform, thus, each column of the matrix $U$ is orthogonal which means its beams can evenly divide the entire 3D space. As a result, the matrix $U$ is defined as [8]

$$U = [a(\psi_1, \psi_2)]^H,$$

(4)

where $\psi_1 = i/N_1$ for $i \in \mathbb{T}(N_1)$ and $\psi_2 = j/N_2$ for $j \in \mathbb{T}(N_2)$ are the spatial azimuths and elevations predefined by the antenna array, respectively. Thus, the transformed 3D massive MIMO system model can be represented as

$$\tilde{y} = H^H U^H P s + v = \tilde{H}^H P s + v,$$

(5)

where $\tilde{y}$ is signal vector received under the beamspace, and the beamspace channel $\tilde{H}$ can be defined as

$$\tilde{H} = [\tilde{h}_1, \tilde{h}_2, \cdots, \tilde{h}_K] = U H,$$

(6)

where $\tilde{h}_k$ is the beamspace channel of the $k^a$ user, the $N$ rows of $\tilde{H}$ correspond to $N$ orthogonal beams as mentioned above whose spatial elevation direction are $\bar{\theta}_1, \bar{\theta}_2, \cdots, \bar{\theta}_N$, and in this paper, we assume that the spatial azimuth direction is fixed. Note that the number of users in the marine area is sparse in a certain period of time, thus the signal received by the BS within this time is also sparse. We can select some dominant beams from the sparse beamspace channel to reduce the
dimension of massive MIMO system without causing the reduction of sum rate. It is worth mentioning that this not only avoids obvious performance loss, but also the overhead of the system is reduced greatly.

3. Achievable sum rate

The received symbol of the $k^{th}$ user in the $n^{th}$ beam in massive MIMO system can be expressed as

$$
y_{k,n} = h_{k,n}^H u_n \sqrt{P_{k,n}} + h_{k,n}^H u \sum_{i=1}^{\lfloor \frac{|\mathcal{S}|}{2} \rfloor} \sqrt{P_{i,n}} + v_{k,n}
$$

(7)

where $u_n$ is the $n^{th}$ column of $U_n$, and $U_n$ is the precoding (beamforming) matrix in this paper, $\lfloor \frac{|\mathcal{S}|}{2} \rfloor$ represents the number of total users served by the $n^{th}$ beam.

Then, according to (7), the SINR at the $k^{th}$ user in the $n^{th}$ beam can be presented as

$$\psi_{k,n} = \frac{\|h_{k,n}^H u_n\|_2^2 p}{\zeta_{k,n}},$$

(8)

where

$$\zeta_{k,n} = \|h_{k,n}^H u_n\|_2^2 p + \sum_{j=1}^{\lfloor \frac{|\mathcal{S}|}{2} \rfloor} \|h_{k,n}^H u\|_2^2 p + \sigma^2.$$

(9)

Finally, the achievable sum rate of the $k^{th}$ user in the $n^{th}$ beam is

$$R_{k,n} = \log_2(1 + \psi_{k,n}).$$

(10)

As described in the first section, we schedule a user for service within each beam. Now we select a scenario at sea for analysis and put the beams and users into set $\mathcal{S} = \{1,2,\cdots,N_2/2\}$ and set $\mathcal{T} = \{1,2,\cdots,K\}$, respectively. Our target is to select a combination of beam from set $\mathcal{S}$ to serve a combination of user from set $\mathcal{T}$ which can achieve the maximum sum rate. According to (6), the problem of joint users and beams selection can be formulated as

$$\mathcal{U}^{opt}, \mathcal{B}^{opt} = \arg\max_{\mathcal{U} \subseteq \mathcal{T}} \max_{\mathcal{B} \subseteq \mathcal{S}} \sum_{k \in \mathcal{U}} \sum_{b \in \mathcal{B}} \lambda_k \log(1 + \frac{\|h_{k,b}^H u_b\|_2^2 p}{\zeta_{k,b} + \sigma^2}).$$

(11)

where

$$\lambda_k$$

is a weighting factor, which is related to the priority of the scheduling user, the higher the priority, the larger the weighting factor. $p = P/|\mathcal{A}|$ is transmitted power for each user, and $c_k$ is the beam which user $k$ falls in. $\mathcal{U}^{opt}$, $\mathcal{B}^{opt}$ are the set of users and the set of beams when the achievable sum rate is maximum, respectively.

4. Joint user scheduling and beam selection

It is known that the best scheme is to use the exhaustive method, but the huge computational complexity it brings is unacceptable which involves $\sum_{i=1}^{\lfloor \frac{|\mathcal{S}|}{2} \rfloor} \sum_{i=1}^{\lfloor |\mathcal{T}| \rfloor}$. To reduce the computational complexity, a scheme of joint user scheduling and beam selection has been proposed to achieve the near-optimal sum rate. We assume all the users falling within in some beams. Considering the limitations of analog beams, we schedule a user to serve in each beam. To
achieve the maximum sum rate, the users we scheduled is closest to the BS in each beam and assume weighting factor $\lambda_k = 1$, where $k = 1, 2, \cdots, K$. Then, we use the greedy algorithm to select the best user combination for the scheduled users to serve. And the joint user scheduling and beam selection will give a one-to-one correspondence between the users’ location information and the beams which we will selected and the complexity of the proposed scheme is greatly reduced. Finally, the set of the proposed scheme can be presented as

$$\hat{U}^{opt}, \hat{B}^{opt} = \arg \max_{U \subseteq \hat{U}, B \subseteq \hat{B}} R$$

(13)

where

$$R = \sum_{k \in \hat{U}} \log(1 + \frac{\|h_k^H u_i\|^2 p}{\sum_{i \in B \setminus \{c_k\}} \|h_k^H u_i\|^2 p + \sigma^2}).$$

(14)

with $\hat{U}, \hat{B}$ as the set of selected users and beams by the scheme we proposed.

**Figure 2.** Schematic diagram of two-ray and three-ray propagation in the marine.

Now we consider a system model of a sea area, as mentioned in Section II. Then we use a planar antenna array with a dimension of $N_1 \times N_2$, the vertical angular space is divided into $N_2$ equal parts, and the angle of each parts (beam) is $\pi / N_2$. Considering the particularity of the user at sea, there are $K$ users randomly distributed on the same shipping lane, we can know the location information of users through AIS. According to the corresponding relation between the location of users and beams, we can know which beam the user falls in. Taking into account the critical boundary point between the 2-ray channel model and the 3-ray channel model [9], we call this point as break point, remember as $D_{break}$ [10]:

$$D_{break} = \frac{4h_b h_i}{\lambda}.$$  

(15)

where $h_b$ stands for the height of the base station, $h_i$ stands for the height of the user receiving antenna, and $\lambda$ denotes the wavelength of carrier. The 2-ray channel model is used by the users who will be served within $D_{break}$, and the 3-ray channel model is used by the users who will be served beyond $D_{break}$. As show in Figure 2, the user’s direct ray under the 2-ray model is in the same beam as another user’s reflection ray under the 3-way model which resulting in intra-beam interference. The coverage area of each beam [12] is shown in Figure 3.
Figure 3. Model of the coverage of each beam

We can calculate the farthest distance covered by each beam:

\[ D_{B_1} = (h_i - h_f) \times \arctan(\pi / N_2), \]
\[ D_{B_2} = (h_i - h_f) \times \arctan(2\pi / N_2) - D_{B_1}, \]
\[ D_{B_3} = (h_i - h_f) \times \arctan(3\pi / N_2) - D_{B_1} - D_{B_2}, \]
\[ \vdots \]
\[ D_{B_{N/2}} = (h_i - h_f) \times \arctan(\pi / 2) - D_{B_1} - D_{B_2} - \cdots - D_{B_{N/2-1}}. \]

(16)

Then, the coverage area of the 1st beam is 0 - \( D_h \), the coverage area of the 2nd beam is \( D_h - D_{B_1} \), ..., the coverage area of the \((N/2)th\) beam is \( D_{B_{N/2-1}} - D_{B_{N/2}} \). According to the distance within \( D_{break} \) and beyond \( D_{break} \), we can calculate which beams will fall within this range, and only consider the users fall within the selected beams. Then, in each beam, we select the user closest to the BS which guarantee the maximum rate. Finally, we choose user combination by for the greedy search method to achieve the maximum value. Compared with the greedy search method, the proposed scheme achieves much better trade-off between the performance and computational complexity. To understand this scheme clearly, we summarize the procedure of the joint user scheduling and beam selection in Algorithm 1.

Now we can calculate the computational complexity of the scheme is \( \sum_{i=0}^{\left\lceil B^{opt} \right\rceil} [B^i] - i \), where \( B^{opt} \in [1, B] \), \( B \) is a beam set within a user in it, and the number of elements is less than \( N/2 \).

Algorithm 1 Joint user scheduling and beam selection

**Initialization:** Users set \( U = \emptyset \), beams set \( B = \emptyset \), set \( \chi_i = \emptyset \) is the distance between user and the BS in \( i \)th beam, \( i = 1, 2, \ldots, N/2 \), where \( \emptyset \) is the empty set, each user is in the corresponding beam.

**Step 1:** Calculate the coverage area of each beam according to (16).

**Step 2:** Based on the user’s location information, put users into the corresponding beam.

For \( k = 1, 2, \ldots, K \) do

For \( i = 1, 2, \ldots, N/2 - 1 \) do

If \( D_i \in (D_{B_{i-1}}, D_B) \) then

\( \chi_i \leftarrow \chi_i \cup \{D_i\} \),

\( U_i \leftarrow U_i \cup \{k\} \),

End if

End for

End for

**Step 3:** Select the user which closest to the BS in each beam.

For \( i = 1, 2, \ldots, N/2 - 1 \) do
\[ k^* = \arg \min_{k \in \mathbb{K}} \chi_k, \]
\[ \mathcal{U} \leftarrow \mathcal{U} \cup \{k^*\}. \]

End for

**Step 4:** Select the beams corresponding to the users in set \( \mathcal{U} \) and put the selected beams into set \( \mathcal{B} \).

**Step 5:** We can obtain the set of joint user scheduling and beam selection \( \mathcal{U}^{\text{opt}}, \mathcal{B}^{\text{opt}} \) according to (13).

5. Simulation results

In this section, we will present the simulation results to demonstrate the advantage of the proposed scheme. Specifically, we take a typical offshore communication system into consideration where the BS is equipped with an UPA of 256 antennas where there are \( N_1 = N_2 = 16 \) antennas in the vertical and horizontal directions, respectively. At present, we assume that there are total \( K \) users shipping on the same sea channel. The transmitted power is set from 0dBm to 40dBm. We take the channel parameters of \( k \)th user into consideration as: 1) \( \alpha_{\ell,k} \sim \mathcal{CN}(0,1) \) for \( 1 \leq \ell \leq 3 \); 2) \( D_k \) follow the uniform distribution within \([100m, 8000m]\). The height of the BS is 100m, the height of the antenna on each ship is 10m and the height of the evaporation waveguide layer is 140m. In addition, we also propose a similar joint user scheduling and beam selection scheme as a comparison. As previously stated, we have known which beam the users fall in and within each beam, we select a random user to serve. Since the transmission mode is unchanged, the reflection ray of the evaporating waveguide layer in the 3-ray channel model enhances the received signal compared to the 3-ray channel model. Therefore, we simulate under the 3-ray channel model. In the simulations, we consider the following schemes for comparison: (1) “exhaust search method (ESM)”, where traversing all the possible combinations of \( K \) users and select the maximum achievable sum rate combination. (2) “Algorithm 1”, the scheme we proposed where traversing all combinations of choosing the nearest user from the base station in each beam and select the maximum achievable sum rate combination. (3) “Algorithm 2”, a similar scheme we proposed as comparison where traversing all combinations of an arbitrary selection of users inside each beam and select the maximum achievable sum rate combination. (4) “arbitrary selection method (ASM)”, where users are selected randomly and calculate their sum rate.

Figure 4. Achievable sum rate against transmitted power P, where the number of users is 10.

Figure 4 shows the performance of four schemes as mentioned above, where the number of users is \( K = 10 \) in the 3-ray channel model, and the transmitted power by BS is 10W. We can find Algorithm 1 do better than Algorithm 2 in performance. It is intuitive that exhaust search method can achieve the best achievable sum rate, however, the proposed joint user scheduling and beam selection is greatly reduced in computational complexity and when the BS transmitted power is relatively low, we can see the performance is close to the exhaust search method. Users are selected randomly to service suffers from the worst sum rate.
Figure 5. Achievable sum rate against the number of users K, where transmitted power $P$ at the BS is 10W.

Observe from Figure 5, as the number of users increases, we can see that the proposed joint user scheduling and beam selection and the exhaust search scheme are increasing at nearly the same sum rate. When the number of users served is small, the proposed two schemes achieve little difference in the sum rate. As a comparison, Algorithm 2 is slightly reduced in performance compare to the first two methods. Finally, the scheme we select random users to serve is the worst in performance because as the number of arbitrary serviced users increases, the interference will become more seriously.

6. Conclusions

In this paper, we considered maritime large-scale antenna system using analog beamforming. To further reduce the inter-beam interference, we proposed joint user scheduling and beam selection to maximize the users’ achievable sum rate. Considering the sea area, each ship is equipped with AIS, we can get the location information of each ship. Comparing with the traditional methods, we schedule users and select beams using the location information which greatly reduces the complexity. In the future, we will expand the scope of the study to multiple waterways, and introducing no-northogonal multiple access space (NOMA) which can further improve the achievable sum rate.

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