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Beam selection for mm-wave massive MIMO systems using ACO & combined digital precoding under hybrid transceiver architecture

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Abstract: We propose a Wiener filter (WF) and a combined zero forcing (ZF)/WF precodings with ant colony optimization (ACO) algorithms as the digital precoder for millimeter wave multiple-input multiple-output (MIMO) systems. In the proposed schemes, beams are selected based on maximal magnitude (MM) criteria and the selection is optimized using ACO algorithm to achieve near optimal solution with highly reduced complexity. According to the simulation results, while ACO-WF scheme achieves higher sum rate in high inter-user interference (IUI) environments compared with conventional precoders, we confirm ACO-ZF/WF scheme can obtain a maximal sum rate in both low and high IUI environments.

Keywords: millimeter wave, MIMO, ACO algorithm, zero forcing, Wiener filter

Classification: Antennas and Propagation

References

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1 Introduction

Beamspace massive MIMO, considered in this literature, is the hybrid architecture where conventional antenna space is converted into beamspace to produce predefined beams using discrete lens array (DLA) in the analog domain [1]. With millimeter wave (mm-wave) massive MIMO, the channel becomes sparse and not all the beams contribute to the overall system performance as such, beam selection is important to reduce hardware cost, complexity, and power consumption further while maintaining reasonable system performance.

Selecting beams using maximal magnitude (MM) has low complexity however, it ignores the inter-user interference (IUI) which limits its performance in multi-user systems. Although the best way to find optimal beams is to use exhaustive search, it is prohibited due to its high computational complexity in massive MIMO systems. Beam selection using MM, ant colony optimization (ACO) and zero forcing (ZF) as digital precoder (ACO-ZF) was proposed [1]. ZF precoder completely eliminates IUI and results in a higher sum rate when IUI level is low. However, the performance degrades when interference becomes very high because it reduces the received signal power at the receiver due to its noise enhancement feature.

In this study, we propose a Wiener filter (WF) based precoder and beam selection using MM and ACO (ACO-WF) [2]. Although WF-ACO produces higher sum rate in high IUI region than ACO-ZF does, it provides lower sum rate in low IUI region. Thus, we also propose a combined precoding scheme of ZF and WF as the dual digital precoder. Through computer simulation, the proposed combined precoding scheme results in a system sum rate superior to the system sum rate when ZF or WF precoding is used alone as a digital precoder in a low and high IUI environment.

2 System model

We consider a base station (BS) with N antennas serving K single antenna users in a downlink mm-wave beamspace massive MIMO multi-user scenario, which is the same as that in the literature [1] and its parameters used in simulation are as in Table I shown in Section 5. The users are randomly located in a circular area of radius L at a distance D from the BS.

The received signals by the K users are given by [1]:

$$\mathbf{y} = \mathbf{H}^H \mathbf{U} \mathbf{F}_{BB} \mathbf{x} + \mathbf{n} \quad (1)$$

where $\mathbf{H} = [\mathbf{h}_1, \dots, \mathbf{h}_K]$ is an $N \times K$ channel matrix, where \mathbf{h}_k for $k = 1, \dots, K$ is the channel vector for the k -th user, \mathbf{U} is an $N \times K$ discrete fourier transform (DFT) matrix as the analog precoder, \mathbf{n} is an $N \times 1$ additive white Gaussian noise (AWGN) vector whose entries are Gaussian random variables with zero mean and variance σ^2 , \mathbf{F}_{BB} is an $N \times K$ digital precoding matrix, \mathbf{x} is an $N \times 1$ transmitted complex signal vector. We use the same channel model to generate the components of \mathbf{h}_k as used in the literature [1].

The beamspace MIMO channel $\tilde{\mathbf{H}}$ becomes:

$$\tilde{\mathbf{H}} = [\tilde{\mathbf{h}}_1, \tilde{\mathbf{h}}_2, \dots, \tilde{\mathbf{h}}_K] = [\mathbf{U}^H \mathbf{h}_1, \mathbf{U}^H \mathbf{h}_2, \dots, \mathbf{U}^H \mathbf{h}_K] \quad (2)$$

where $\tilde{\mathbf{h}}_k$ is the beamspace channel vector of the k -th user. The elements of $\tilde{\mathbf{h}}_k$ represents the N orthogonal pre-defined beams. The number of dominant beams is much smaller than N due to the sparse structure of the beamspace channel. As such, K beams are selected to reduce the MIMO system dimension to form $K \times K$ channel matrix $\tilde{\mathbf{H}}_r$ with no performance loss such that $\tilde{\mathbf{H}}_r = \tilde{\mathbf{H}}(m, :)_{m \in R}$, where R is the set of selected dominant beams based on MM criteria. The dimension reduced beamspace MIMO downlink received signals of K users are given by:

$$\tilde{\mathbf{y}}_r = \tilde{\mathbf{H}}_r^H \tilde{\mathbf{F}}_{BB} \mathbf{x} + \mathbf{n} \quad (3)$$

where $\tilde{\mathbf{F}}_{BB}$ is the $K \times K$ dimension reduced precoding matrix and has the constraint of $E\{\|\tilde{\mathbf{F}}_{BB} \mathbf{x}\|_2^2\} = \rho$ and ρ is the transmit power at the BS.

3 Precoder matrix and sum rate maximization

Low complexity BS system is the main focus of this work. For the purpose, ZF precoder is proposed as [1]:

$$\mathbf{F}_{ZF} = \alpha_{ZF} \tilde{\mathbf{H}}_r (\tilde{\mathbf{H}}_r^H \tilde{\mathbf{H}}_r)^{-1}, \quad \alpha_{ZF} = \sqrt{\frac{\rho}{\text{tr}((\tilde{\mathbf{H}}_r^H \tilde{\mathbf{H}}_r)^{-1})}} \quad (4)$$

To improve the sum rate performance in high IUI area, we propose Wiener filter based precoder as [2]:

$$\mathbf{F}_{WF} = \alpha_{WF} \mathbf{F}, \quad \mathbf{F} = (\tilde{\mathbf{H}}_r \tilde{\mathbf{H}}_r^H + \zeta \mathbf{I})^{-1} \tilde{\mathbf{H}}_r, \quad \zeta = \frac{\sigma^2 K}{\rho},$$

$$\alpha_{WF} = \sqrt{\frac{\rho}{\text{tr}(\mathbf{F} \mathbf{F}^H)}} \quad (5)$$

Even though WF outperforms ZF at low and high SNR, the sum rate performance of WF becomes lower than ZF at low IUI environment and it increases higher than ZF when IUI becomes higher. Based on this characteristic, a combined ZF/WF precoder is also proposed in this work. According to used criteria, the precoders \mathbf{F}_{ZF} and \mathbf{F}_{WF} are replaced by $\tilde{\mathbf{F}}_{BB}$ in (3).

Assuming equal transmit power at the BS, the average rate of the k -th user is given by $R_k = \log_2(1 + \gamma_k)$, where γ_k is the signal-to-interference plus noise power ratio (SINR) of the k -th user [3]. The sum rate becomes $R^{sum} = \sum_{k=1}^K R_k$. The optimal beams \tilde{H}_r^{opt} are selected based on:

$$\tilde{H}_r^{opt} = \arg \max_R R^{sum} \quad (6)$$

The best solution to obtain \tilde{H}_r^{opt} is to use exhaustive search. However, since its computational complexity in massive MIMO systems is prohibitive, a low complexity beam selection algorithm is crucial to obtain a sub-optimal \tilde{H}_r^{opt} .

4 Beam selection optimization using ACO algorithm

To achieve a near optimal solution of beam selection, we use ACO as a low complexity algorithm. Due to channel sparsity, D_k dominant beams are used for the k -th user beam selection such that D_k is smaller than the number of pre-defined beams. The index set is given by $D_k = \{I_{k1}, \dots, I_{kD_k}\}$. For the t -th iteration, the cost function d_{kd}^t is used to determine the suitability of the d -th beam in D_k .

From (4) and (6), the cost function for ACO-ZF scheme is given by [1]:

$$d_{kd}^t = \text{tr}(((\tilde{\mathbf{H}}_{r,k}^{t-1})^H \tilde{\mathbf{H}}_{r,k}^{t-1} + \bar{\mathbf{H}})^{-1}) \quad (7)$$

and from (5) and (6), the cost function for ACO-WF scheme is given by [2]:

$$d_{kd}^t = \text{tr} \left(\left(\tilde{\mathbf{H}}_{r,k}^{t-1} (\tilde{\mathbf{H}}_{r,k}^{t-1})^H + \frac{(K-1)}{\rho} \mathbf{I} + \bar{\mathbf{H}} \right)^{-1} \right) \quad (8)$$

where $\tilde{\mathbf{H}}_{r,k}^{t-1}$ is a $(K-1) \times K$ matrix obtained by omitting the k -th row of $\tilde{\mathbf{H}}_r^{t-1}$, which represents the channel matrix obtained at the $(t-1)$ -st iteration, and $\bar{\mathbf{H}} = \tilde{\mathbf{h}}(I_{kd}, :)^H \tilde{\mathbf{h}}(I_{kd}, :) + \varsigma \mathbf{I}$ where $\tilde{\mathbf{h}}(I_{kd}, :)$ is the I_{kd} -th row of the full dimension beamspace channel matrix $\tilde{\mathbf{H}}$ and ς is a positive number to impose the existence of matrix inversion.

To determine the cost function for ACO-ZF/WF, we first set a threshold ψ from the sum rate performances, then select (7) if $\psi \leq K$ or (8) if $\psi > K$.

The cost function for ACO-ZF, ACO-WF, and ACO-ZF/WF is then converted into their heuristic values by:

$$\eta_{kd}^t = \sqrt{e^{-d_{kd}^t/N^2}}. \quad (9)$$

Then the BS selects the beam for each user based on the probability:

$$p_{kd}^t = \frac{[\tau_{kd}^{t-1}]^a [\eta_{kd}^t]^b}{\sum_{d=1}^{D_k} [\tau_{kd}^{t-1}]^a [\eta_{kd}^t]^b} \quad (10)$$

where a and b are positive constants, and τ_{kd}^{t-1} is the positive feedback of the previous selection. The beam with the highest probability is selected for the k -th user. Then the feedback is updated after the beam selection by:

$$\tau_{kd}^t = (1 - \Gamma)\tau_{kd}^{t-1} + \omega \eta_{kd}^t p_{kd}^t \quad (11)$$

where ω is a weight factor and Γ is a decay parameter whose value is between 0 and 1. Higher probability and heuristic value increase the positive feedback faster and thus a sub-optimal solution can be reached faster with increasing iterations. The modified ACO algorithm is shown in Algorithm 1.

Algorithm 1 ACO algorithm for beam selection

Input: $\tilde{\mathbf{H}}, D_k, \forall k, T_{\max}, a, d, \Gamma, \omega, \psi$

Output: $\tilde{\mathbf{H}}_r$

- 1: $R^0 = \{I_1^0, \dots, I_K^0\}; \tilde{\mathbf{H}}_r^0 = \tilde{\mathbf{H}}(m, :)_{m \in R^0}; \text{tr} = \infty; \eta_{kd}^t = 1, \forall t, \forall k, \forall d.$
- 2: **for** $t = 1$ to T_{\max} **do**
- 3: $R^t = R^{t-1};$
- 4: **for** $k = 1$ to K **do**
- 5: **for** $d = 1$ to D_k **do**
- 6: **if** $K \leq \psi$ **then**
- 7: Calculate d_{kd}^t according to (7);
- 8: **else**
- 9: Calculate d_{kd}^t according to (8);
- 10: **end if**
- 11: Calculate η_{kd}^t and p_{kd}^t according to (9) and (10), respectively;

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12:   Update  $\tau_{kd}^t$  according to (11);
13:   end for
14:   Select maximum  $p_{kd}^t, \forall d$ . Update index  $d_{max}$  in  $R^{t-1}$ ;  $I_k^{t-1} = I_{kd_{max}}$ ;
15:   if  $d_{kd_{max}} \leq \text{tr}$  then
16:      $\text{tr} = d_{kd_{max}}, \tilde{\mathbf{H}}_r^t = \tilde{\mathbf{H}}(m, :)_{m \in R^{t-1}}$ ;
17:   else
18:      $\tilde{\mathbf{H}}_r^t = \tilde{\mathbf{H}}(m, :)_{m \in R^t}$ ;
19:   end if
20: end for
21: end for
22: Return  $\tilde{\mathbf{H}}_r$ 

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Table I. Simulation parameters

Parameter	Value	Parameter	Value (ZF)	Value (WF)
Distance D	150	a	0.8	1
Radius L	10	b	0.4	2
No. of cluster N_c	3	$\alpha_{k,0}$	-3 dB	-3 dB
ω	0.5	$\alpha_{k,i,l}$	-5 dB	-5 dB
Angular spread AS	5°	Decay Γ	0.3	0.3
No. of rays N_r	$\mathcal{U}[1, 30]$	σ^2	1	1

5 Numerical results

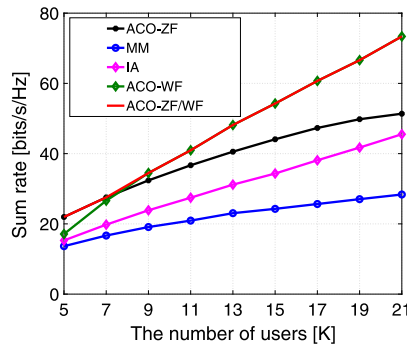
The sum rates of the proposed schemes ACO-WF [2] and ACO-ZF/WF are evaluated and compared to ACO-ZF [1], interference-aware (IA), and MM schemes in this section. The simulation parameters are listed in Table I. We use the same channel parameters as those in [1].

The BS is with $N = 30$ beams, while K user terminals are with single antenna. Using ACO, 1 beam per user terminal is attained.

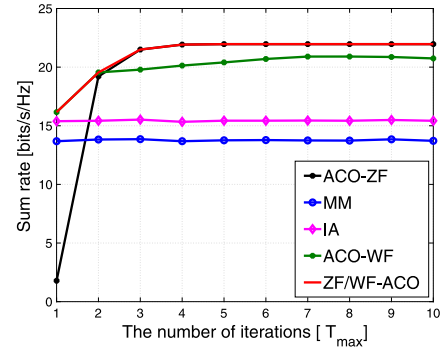
We show sum rates versus K from 5 to 21 in Fig. 1a. From the figure, we can see that the sum rate by ACO-ZF is better than that by ACO-WF when $K \leq 8$. Thus, we set the threshold as $\psi = 8$ for ACO-ZF/WF. From Fig. 1a, it can be seen that the proposed scheme of ACO-ZF/WF achieves higher sum rate compared to IA and MM schemes. When $K \leq \psi$, ACO-ZF is selected as the precoder and when $K > \psi$, ACO-WF is selected as the precoder. By selecting one precoder at a time, the sum rate can be maximised in both low and high IUI environments.

In Fig. 1b, sum rate comparison against number of iterations is shown in a low IUI scenario, where $N = 30$ and $K = 5$, i.e., $K \ll N$. Then for ACO-ZF/WF, ZF would be the precoder of choice. This scheme only requires 3 iterations to reach the maximum sum rate.

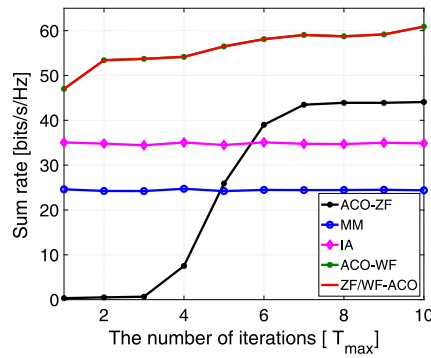
In Fig. 1c, sum rate comparison against number of iterations is shown in high IUI scenario. In this scenario, we consider $N = 30$ and $K = 15$. The precoder of choice becomes WF in ACO-ZF/WF scheme due to the existence of high IUI. With only 2 iterations, a sum rate higher than the other schemes can be achieved.



(a) Sum rate versus number of users K when $N = 30$, $D_k = 8$, $T_{max} = 10$, and $\text{SNR} = 20$ dB.



(b) Sum rate versus number of iterations when $N = 30$, $K = 5$, $D_k = 8$, and $\text{SNR} = 20$ dB.



(c) Sum rate versus number of iterations when $N = 30$, $K = 15$, $D_k = 8$, and $\text{SNR} = 20$ dB.

Fig. 1. Sum rate comparisons of several beam selection schemes

6 Conclusion

Beams are selected using MM and optimized using ACO and the combined precoding scheme in the digital domain is proposed in mm-wave massive MIMO system using DLA in the analog domain. Through simulation results, the proposed ACO-ZF/WF scheme achieved higher sum rate in low and high interference scenarios compared to other schemes.