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Adaptive selection mechanism based on distributed interference alignment

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Abstract: Interference Alignment(IA) technology shows a great potential to improve the capacity of future wireless network immensely, and it becomes a research focus in interference elimination field. Nevertheless, among the existing distributed algorithms like Minimum Interference Leakage(MIL), maximum-SINR (max-SINR) and Minimum Mean Square Error(MMSE), there is no such an optimal solution that could outperform the others throughout the SNR values. Based on a diversity analysis on existing standards, an adaptive selection mechanism is proposed, helping both transmission parties choose the optimal algorithm according to the communication condition. The simulation results show that compared with mono-algorithm, the newly proposed selection scheme can achieve as much as 5 dB SNR gain when the same data rate is obtained.

Key words: distributed interference alignment; channel state information; data rate; SNR value; adaptive selection

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The capacity of wireless communication network used to be considered as interference limited. Nevertheless, the recently emerged interference alignment(IA) technology points out that the capacity is not limited by interference and it could even increase linearly with the growth of user number. In particular, with any sized interference channel with any number of users, the capacity for any given user will scale at half the rate of its interference-free capacity in the high transmit power regime[1]. The key to realize interference alignment lies in the difference of the received signal spaces between different receivers. By utilizing such differences, interfering signals may be designed to cast overlapping shadows at their undesirable receivers; meanwhile, they will remain distinguishable at the receivers where they are desired. Combined with MIMO system which could provide more signal space, it is possible to achieve interference-free transmission for all users. Then the design of the precoding and interference-suppressing matrices at the transmitter and receiver respectively become the main issues.

IA schemes presented in [1] are in the form of closed form expression for the transmitting precoding matrices. However, these solutions suffer from three significant drawbacks. Firstly, the global Channel State Information(CSI) needs to be shared among all the nodes in the network. Secondly, the solvability of the closed form expression is unknown for network that is different from the certain conditions discussed in paper[1]. Thirdly, when the user number increases, the closed form expressions are too complicated to have a solution. To promote the practical applications of the technology, researchers managed to put forward many evolution versions, such as blind IA[2], retrospective IA[3], ergodic IA[4] and minimum squared Euclidean distances between interference and signal[5], of the ideal alignment scheme. Among those new methods, the distributed interference alignment[6] received much more developments and attentions for its implementability in the real scene.

Distributed interference alignment means to make the interfering and the desired signal distinguishable at the receiver only by making use of local CSI. It is more effective when combined with iterative algorithm, which is based on network

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reciprocity and the "minimize interference to others" principle. Starting with arbitrary transmit and receive filters, the receivers iteratively update these filters to approach interference alignment. The quality of alignment is measured by a specific object function. It is distributed in the sense that it minimizes or maximizes the goal at the transmitters and receivers, respectively. And to keep the balance between benefits and implementation complexity, researchers often do not seek to totally align all interferences but allow partial overlaps between interfering signals, that is, partial interference alignment is more cost-effective in most cases. Algorithms like this are promising for both their ability to provide precoding solutions in a practical setting and their flexibility in application to arbitrary networks for which closed-form solutions are unknown[6].

Paper [7] proposed an iterative algorithm that take an altruistic approach to interference management and utilize only the local side information which is available naturally due to the reciprocity of wireless networks. The quality of alignment is measured by the power that residues in the undesirable receiver, i.e., the interference power remaining in the received signal after the interference suppression filter is applied. The goal is to achieve interference elimination by progressively reducing the leakage interference to others. If the leakage interference converges to zero, then interference alignment is feasible. In [8] the direct channel matrices $\boldsymbol{H}[kk]$, through which the desired signal arrives at the intended receiver, are considered to improve coherent combining gain(array gain) for the desired signal. And one such natural extension of the interference alignment algorithm, where the receive filters are chosen to maximize SINR at the receivers instead of only minimizing the leakage interference, is proposed. Its performance at low SNR is significant. Different from the two previous algorithms, paper [9] aimed to design a set of transmitter precoding and receiving matrices that minimize the total Mean Square Errors(MSE) under transmit power constraints.

Among the distributed interference alignment criteria that have been studied, however, there still has no such an algorithm that could outperform all the others within the whole SNR scope. In this work, an adaptive selection mechanism is considered to achieve optimal interference alignment by making use of the respective advantages of the three criteria. It is accomplished by automatically switching between the algorithms according to different levels of the real-time SNR. Numerical comparisons show that the benefits of adaptive distributed interference alignment algorithm are significant in data-rate view.

The paper is organized as follows. In the next section, the system model considered is illustrated in Fig.1. In section 1, the three interference alignment algorithms are reviewed in existing literature. In section 2, the proposed adaptive selection mechanism based on distributed algorithm and a general procedure diagram is stated. In section 3, the simulation results of the new method are presented and show that it is optimal under the system considered.

1 System model and distributed IA

1.1 System model

A K-user MIMO interference channel is shown in Fig.1 and the received signal can be described by (1):

$$\boldsymbol{Y}_k = \sum_{l=1}^{K} \boldsymbol{H}_{kl}\boldsymbol{X}_l + \boldsymbol{n}_k = \sum_{l=1}^{K} \boldsymbol{H}_{kl}\boldsymbol{V}_l\boldsymbol{s}_l + \boldsymbol{n}_k = \boldsymbol{H}_{kk}\boldsymbol{V}_k\boldsymbol{s}_k + \sum_{l\neq k} \boldsymbol{H}_{kl}\boldsymbol{V}_l\boldsymbol{s}_l + \boldsymbol{n}_k,\ \forall k \in K \quad (1)$$

Where $\boldsymbol{Y}_k$ is the $N_k \times 1$ output vector at receiver k, N_k,M_k, and D_k represent transmit antenna number, receive antenna number and the degree of freedom of user k, respectively. $\boldsymbol{H}_{kl}$ is the $N_k \times M_l$ matrix of channel coefficients between transmitter l and receiver k, $\boldsymbol{V}_k$ is the $M_k \times D_k$ precoding matrix at transmitter k, $\boldsymbol{s}_k$ represents the data streams transmitted from transmitter k. $\boldsymbol{n}_k$ is the $N_k \times 1$ Additive White Gaussian Noise(AWGN) vector at receiver k, $\boldsymbol{n}_k \sim CN\left(0,\delta_n^2 I\right)$. The transmitter power constraint at each node is $E[\|X_1\|^2] = P_l$.

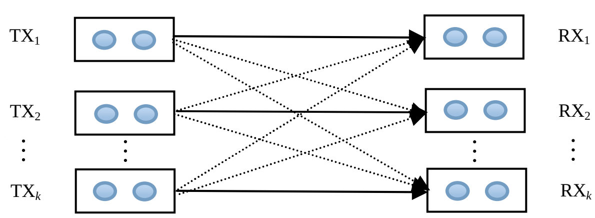

Fig.1 The k-user MIMO interference channel. Transmitter k, with M_k antennas, has a message for receiver l with N_l antennas. All transmitters share a channel with all receivers

Switching the role of transmitters and receivers, the reciprocal communication model of the system defined above is obtained.

$$\overleftarrow{\boldsymbol{Y}}_k = \sum_{l=1}^{K} \overleftarrow{\boldsymbol{H}}_{kl} \overleftarrow{\boldsymbol{X}}_l + \overleftarrow{\boldsymbol{n}}_k = \sum_{l=1}^{K} \overleftarrow{\boldsymbol{H}}_{kl} \overleftarrow{\boldsymbol{V}}_l \overleftarrow{\boldsymbol{s}}_l + \overleftarrow{\boldsymbol{n}}_k = \overleftarrow{\boldsymbol{H}}_{kk} \overleftarrow{\boldsymbol{V}}_k \overleftarrow{\boldsymbol{s}}_k + \sum_{l \neq k} \overleftarrow{\boldsymbol{H}}_{kl} \overleftarrow{\boldsymbol{V}}_l \overleftarrow{\boldsymbol{s}}_l + \overleftarrow{\boldsymbol{n}}_k \text{ ,} \forall k \in K \tag{2}$$

Where, the left arrow on top indicates the corresponding variables o n the reciprocal channel: $\overleftarrow{\boldsymbol{Y}}_k$ is the $N_k \times 1$ output at receiver k on the reciprocal channel, and so are the other variables.

Except for the reverse of the communicating direction, nothing changed to the representative meaning of the variables, introduction is henceforth suppressed to avoid cumbersome notation.

1.2 Distributed interference alignment

1.2.1 MIL

In [7], an iterative interference leakage minimization algorithm is proposed and the iteration objection is to minimize the power in the leakage interference at each receiver, i.e. the interference power remaining in the received signal after the interference suppression filter $\boldsymbol{U}_k$ is applied. The post-processing signal at receiver k can be expressed as $\boldsymbol{R}_k = \boldsymbol{U}_k^{\mathrm{H}} \boldsymbol{Y}_k$ and the total interference leakage at receiver k coming from other transmitters is defined below in (3):

$$\boldsymbol{I}^{[k]} = Tr[\boldsymbol{U}_k^{\mathrm{H}} \boldsymbol{Q}^{[k]} \boldsymbol{U}_k] = Tr[\boldsymbol{U}_k^{\mathrm{H}} \sum_{\substack{j=1, \\ j \neq k}}^{K} \boldsymbol{H}_{kj} \boldsymbol{V}_j \boldsymbol{V}_j^{\mathrm{H}} \boldsymbol{H}_{kj}^{\mathrm{H}} \boldsymbol{U}_k] \tag{3}$$

Where $\boldsymbol{Q}^{[k]}$ is the interference covariance matrix at receiver k.

Under the assumption of channel reciprocity, transmitters and receivers take turn adjusting their beam-forming vectors to reduce the interference leakage. The solution could be resolved through calculating the conjugate gradient of $\boldsymbol{I}^{[k]}$ for $\boldsymbol{V}_k$ and $\boldsymbol{U}_k$, respectively.

$$\begin{aligned} &\boldsymbol{U}_{k,*d} = \upsilon[\boldsymbol{Q}^{[k]}], \qquad d = 1,2,\cdots,d_k \\ &V_{j,*d} = \overleftarrow{\boldsymbol{U}}_{\mathrm{j},*d} = \upsilon[\overleftarrow{\boldsymbol{Q}}^{[k]}], \qquad d = 1,2,\cdots,d_k \end{aligned} \tag{4}$$

1.2.2 Max-SINR

In [8], the receive filters $\boldsymbol{U}_k$ and $\overleftarrow{\boldsymbol{U}}_k$, corresponding to the origion channel and the reciprocal channel repectively, are chosen to maximize SINR at the receivers instead of only minimizing the leakage interference. The max-SINR algorithm iteratively exchanges the role of transmitters and receivers in the network, in the reverse direction, the beam-formers act as receive filters and the receive filters are used as beam-formers. The authors have also taken the inter-stream interference into consideration for each transmit/receive pair and solved for the precoding and receiver matrices one column at a time. Thus the SINR of the l_{th} stream of the k_{th} receiver is:

$$\mathrm{SINR}_{kl} = \frac{\boldsymbol{U}_{k,*l}^{\mathrm{H}} \boldsymbol{H}_{kk} \boldsymbol{V}_{*l} \boldsymbol{V}_{*l}^{\mathrm{H}} \boldsymbol{H}_{kk}^{\mathrm{H}} \boldsymbol{U}_{k,*l}}{\boldsymbol{U}_{k,*l}^{\mathrm{H}} \boldsymbol{B}_{kl} \boldsymbol{U}_{k,*l}} \tag{5}$$

Where $\boldsymbol{B}_{kl} = \sum_{j=1}^{K} \sum_{d=1}^{d_j} \boldsymbol{H}_{kj} \boldsymbol{V}_{j,*d} \boldsymbol{V}_{j,*d}^{\mathrm{H}} \boldsymbol{H}_{kj}^{\mathrm{H}} - \boldsymbol{H}_{kk} \boldsymbol{V}_{k,*l} \boldsymbol{V}_{k,*l}^{\mathrm{H}} \boldsymbol{H}_{kk}^{\mathrm{H}} + \boldsymbol{I}_{N[K]}$, $\boldsymbol{U}_{k,*l}$ represents the column of user k's precoding matrix.

There is no proof that the SINR algorithm will converge, yet no examples are known in which it fails to converge. The update procedure consists of computing the receive filters that maximize the received SINR according to the following equation.

$$\boldsymbol{U}_{k,*l} = \frac{(\boldsymbol{B}_{kl})^{-1} \boldsymbol{H}_{kk} \boldsymbol{V}_{k,*l}}{\left\| (\boldsymbol{B}_{kl})^{-1} \boldsymbol{H}_{kk} \boldsymbol{V}_{k,*l} \right\|} \tag{6}$$

The variables in (6) are reverted when calculating the receive filter $\overleftarrow{\boldsymbol{U}}_k$ on the reciprocal. Though max-SINR has significant performance at low and moderate SNRs, its efficiency at high SNRs is poor due to the negligence of the correlationship between the transmitted data streams. This is a possible researching point for future work.

1.2.3 MMSE

Literature [10] provides a new interference alignment scheme for the MIMO interference channel through joint transceiver design. The paper designed a set of transmitter precoding and receiving filter matrices that minimize the total MSE under the individual transmit power constraints. For the k_{th} user, the mean square error MSE_k can be calculated as:

$$\mathrm{MSE}_k = E[\left\| R_k - s_k \right\|^2] = E\left\{ tr[(R_k - s_k)(R_k - s_k)^{\mathrm{H}}] \right\} \tag{7}$$

And for each transmitter, the optimization problem could be expressed as:

$$\begin{aligned}&\min_{V_k,U_k}\sum_{k=1}^{K}\mathrm{MSE}_k\\ &s.t.\quad tr(\boldsymbol{V}_k\boldsymbol{V}_k^{\mathrm{H}})=\boldsymbol{P}_k\qquad \forall k\in K\end{aligned}\tag{8}$$

This algorithm requires the calculation of the Lagrange multipliers λ_k according to the power constraint of each transmitter(i.e. via Newton iteration). The results are given in (9):

$$\begin{aligned}&\boldsymbol{V}_k=(\sum_{l=1}^{K}\boldsymbol{H}_{lk}^{\mathrm{H}}\boldsymbol{U}_l^{\mathrm{H}}\boldsymbol{U}_l\boldsymbol{H}_{lk}+\lambda_k\boldsymbol{I})^{-1}\boldsymbol{H}_{kk}^{\mathrm{H}}\boldsymbol{U}_k^{\mathrm{H}},\qquad \forall k\in K\\ &\boldsymbol{U}_K=\boldsymbol{V}_k^{\mathrm{H}}\boldsymbol{H}_{kk}^{\mathrm{H}}(\sum_{l=1}^{K}\boldsymbol{H}_{kl}\boldsymbol{V}_l\boldsymbol{V}_l^{\mathrm{H}}\boldsymbol{H}_{kl}^{\mathrm{H}}+\delta_n^2\boldsymbol{I})^{-1},\qquad \forall k\in K\end{aligned}\tag{9}$$

1.2.4 Summary

The MIL algorithm guarantees the convergence of the leakage interference, but it may converge to nonzero leakage interference even when IA is feasible[11]. In this case, the MIL algorithm only returns to a solution with local minimal leakage interference. Numerical results in [8] show that max-SINR has good performance especially in terms of low SNR values. IA using the max-SINR algorithm achieves receiving diversity and allows more than one stream of information symbols to be sent by each user[11]. However, no convergence proof is given and it is not clear how to modify it to account for other utility functions. MMSE algorithm has provable convergence and it's straightforward to extend the algorithm to accomodate to different utility functions. Moreover, it can achieve different user priorities by introducing MSE weights. And to achieve fast convergence speed, MMSE needs to follow specific methods when initializing V_k, all of which makes it more complicated in realization.

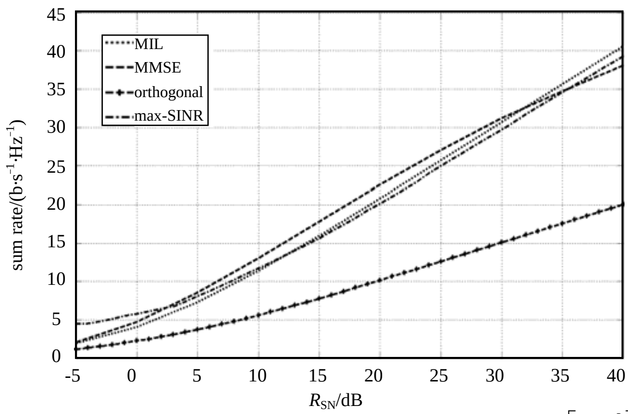

Fig.2 Sum rate performance of the 3 algorithms: K=3, N_k=M_k=2, $E\left[\|X_k\|^2\right]=1$

Here we provide the performance of the algorithms above. The performance is measured by the sum rate achieved over the interference channel, i.e., the sum of the rates achieved by the 3 users, measured in bits per channel use. This paper focuses on case of constant channel coefficients across time and frequency. Further, it must be noted that the number of spatial dimensions (i.e., antennas) in all the nodes is equal to two, in all the systems listed above. The performance is averaged over 200 channel realizations where the channel coefficients are i.i.d. complex Gaussian with unit variance. As shown in Fig.2, significant benefits over the traditional transmitting mode, orthogonal transmission, are obtained with distributed IA.

Note that in the discussion above, IA techniques assumed perfect CSI. However, in practice, CSI at the transmitter is far from perfect due to many factors such as channel estimation error, quantization error, and feedback error/delay. The performance of IA scheme is sensitive to such inaccuracies. So, the influence of imperfect CSI will be the topic for further study.

2　Adaptive selection mechanism

Despite the deficiencies of the criteria, we found a regular pattern from the simulation results: the sum data rate of the three algorithm changes with the increase of SNR value, and one of them will always outperform the other two at certain SNR intervals. It is easy to see that MIL algorithm is asymptotically optimal for the interference channel at high SNR but has suboptimal throughput at low-and-moderate SNR, whereas the MMSE criterion performs well at moderate SNR. What is particularly interesting is the considerable performance of max-SINR algorithm at low SNR.

This is the find that inspired our proposal. Since there is no such an optimal solution throughout the whole SNR range, we can combine the advantages of the three algorithms into one system. It can be realized by adapting the choice of algorithm to the real-time SNR value at the receiver. The SNR range will be divided into several intervals according to the performance of the algorithm considered. In the case of Fig.2, the intervals could be [−5,3), [3,32) and [32,40]. Once the receiver gets its present SNR, it will choose the optimal criterion at this SNR value, then following the iterating steps of the algorithm normally. The general process can be summarized as Fig.3.

Since SNR varies with the transmitting channel, the performance of the new method would be uncertain if the selection of algorithm cannot keep pace with the change of the SNR value, so the selection should be updated over time. And the solution that we put forward is to set a timer to control the reselection process. The timer, which could also be explained as the time interval between each criterion reselection procedure, should be set less than or equal to the corresponding channel correlation time. It will be small when the channel changes fast but larger when the channel is relatively stable. Such a principle can contribute a lot to the efficiency of the scheme since channel state is the main cause for the change of SNR. An update timer can simplify the process when the transmitting condition is pleasant and also guarantee the selected one is always optimal for the receiver when the transmitting condition is harsh.

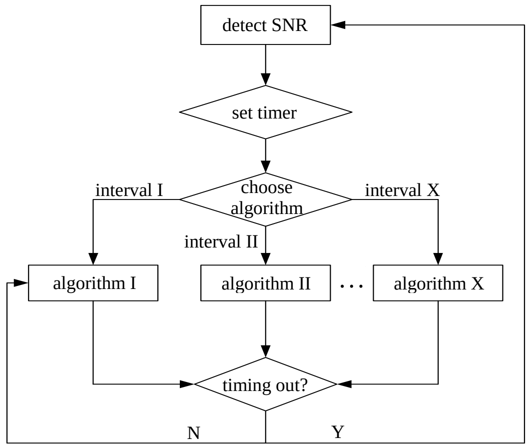

Fig.3 Flow chart of the proposed adaptive selection mechanism

The proposed scheme is not limited to the three algorithms introduced above, any new progress achieved in IA or even interference cancellation can be used in adaptive selection mechanism as an alternative. Besides, the purpose of adaption in this paper is to achieve the largest sum rate of the communication system, once the object function has changed, the choose standards must be changed accordingly, but the general procedure would stay the same. Performance parameters, such as system capacity, bit error rate, implementation complexity and processing time delay, can all be used as the object function.

3 Simulation and Performance

In this section, the performance of the proposed algorithm is simulated. The simulations are performed for the 3-user MIMO interference channel system where each transmitter and each receiver is equipped with two antennas. The channel coefficients are i.i.d. zero mean unit variance circularly symmetric complex Gaussian. The transmit power constraint at each transmitter is P_k=1,k=1,2,3. And in order to present the most detailed aspect of the proposed method, the timer is set to be the unit of SNR changing. The results given below are the averages over 200 independent iterations.

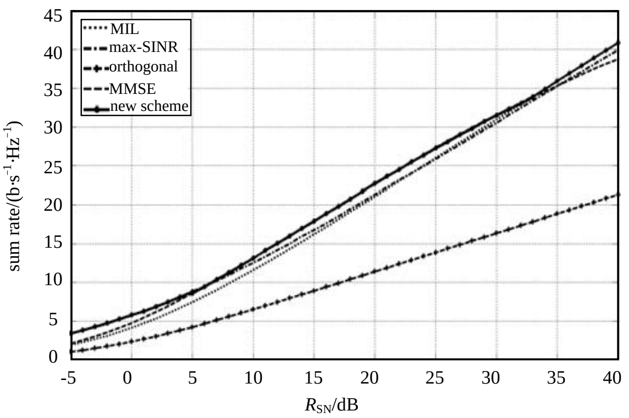

Fig.4 Sum rate performance of the proposed adaptive selection mechanism: K=3, N_k=M_k=2, $E\left[\|X_k\|^2\right]=1$

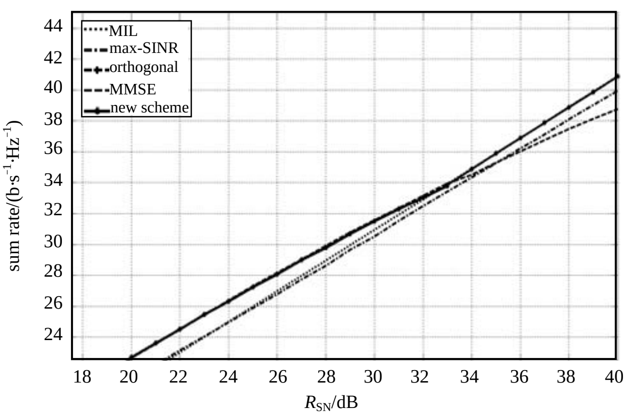

Fig.5 Partial magnification of Fig.4 between SNR interval [20,40]

It can be seen from Fig.4 that the proposed scheme dominates at all SNR. Specifically, max-SINR attains the largest sum rate at low SNR, so the adaptive selection goes to max-SINR in the SNR range of −5 dB to 3 dB. The gain of the selection scheme can be as large as 5 dB, compared to MIL algorithm. Then MMSE remains the optimal alternative between 3 dB and 32 dB and the maximum gain is 3 dB in comparison with max-SINR. For SNR above 32 dB, MIL is the best choice (see Fig.5 for more details).

To sum up, given the same data rate and power constraint, the adaptive selection mechanism based on distributed IA algorithms is always the best one among the three algorithms after adapting selection. Note that the selection is based on the key properties of the existing algorithms, we must have the performance of all the alternatives well in hand before the proposed adaptive selection mechanism is carried out. So, one of the drawbacks of this scheme is that it demands more complexity than using just one algorithm.

4 Conclusion

In this paper, three representative distributed IA algorithms, MIL, max-SINR and MMSE, are studied. We compared the sum rate performances of the three and managed to choose the optimal criterion for different SNR adaptively. The adaptive selection mechanism, with the reselection timer set to be the unit of SNR changing, is proven to be optimal compared to the existing technologies for all SNR. As interference management is a fundamental problem of wireless networks, such asymptotic interference-free transmission algorithms have enormous applications in wireless networks. Future work will focus on reducing the implementation complexity and the influence of imperfect channel estimation on the adaptive selection mechanism.

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基于分布式干扰对齐的自适应选择机制

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摘　要： 干扰对齐技术是未来移动通信系统提高网络容量的一种可能的技术手段，也是目前干扰消除技术的研究热点。现存的研究结果中没有一种准则能够在所有信噪比条件下性能均优于其他算法。在对已有算法进行深入研究的基础上，提出一种自适应选择机制，该机制可以使通信双方根据当前通信条件选择最优准则实现干扰对齐。仿真结果表明，本文所提算法与单一算法相比，在获取相同数据速率的条件下最大可获得 5 dB 的信噪比增益。

关键词： 分布式干扰对齐；信道状态信息；数据速率；信噪比；自适应选择

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