Interference Alignment in Distributed Cooperative Relay System with Delayed CSIT

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ABSTRACT
This paper characterizes the degrees of freedom regions for the multi-user by using interference alignment in a distributed relay system with totally delayed and not too delayed CSI feedback. As a part of the characterization, some new transmission schemes for the relay interference alignment based on the previous Maddah-Ali and Tse (MAT) scheme and Space-Time Interference Alignment (STIA) are proposed. The consequence of the results shows that the achievable gain of sum Degree of Freedom (DoF) can be improved significantly in Delayed Source-Destination channels and ideal Relay-Destination channels, meanwhile, the complexity of Base Station precoding process can be significantly reduced when the quantity of multi-users K is very large. An adaptive linear precoding and MAT combined scheme are also proposed in non-ideal Relay-Destination channels, which aim to simplify the previous MAT precoding process and improve the degree of freedom in different propagation scenarios when partly and totally delayed CSI occur in Relay-Destination channels.

I. INTRODUCTION
In the downlink MU-MIMO scenarios, because of the different positions among every receiving user, multiuser detection technology cannot be adopted to avoid the interference among the different users, and therefore the precoding is a very useful approach to research to control the co-channel interference problem in MIMO systems and so reduce the complexity of receivers. It is well known that from comparison with the transmitter which doesn’t have the CSIT, once the transmitter is aware of the accurate CSIT, the degree of freedom (DoF) of each user can be improved significantly[1]-[3]. However, in real life propagation scenarios the accurate CSIT is very difficult to achieve from the transmitter because of the estimation of the transmitter and plenty of uncertainties in the propagation channels. To solve this problem, Maddah-Ali and David Tse proposed a scenario which shows that the delayed CSIT is also useful in improving the DoF region even though the CSIT is totally different from the current CSI[4]. However, in the basic MAT scheme, it requires that users are provided also with the past channel states of other users. This requires not only CSI estimation and CSIT feedback from the receivers to the transmitter, but also CSI dissemination. Different from the totally pessimist assumption in [4], [5]-[6] considered the mixed CSIT case, which means the transmitter both has the knowledge of perfect and imperfect CSI. A parameter $\alpha$ is introduced to describe the quality of the estimation of CSI, so that the smooth region which connects the pessimism case in [4] ($\alpha = 0$) with the perfect CSIT case ($\alpha = 1$) is achieved. A similar space time interference alignment (STIA) transmitted scheme is also proposed in [7]; they use the linear combined method to cancel the interference once the current and the outdated CSIT are both existing in the transmitter. Similar with [5] and [6], in this paper we studied the interference alignment with mix CSIT case. In order to keep improving the DoF performance of the multi-user and implement the interference alignment scheme more practically and more efficiently when suffering delayed CSIT, we proposed an adaptive precoding scheme to implement the MAT interference alignment scheme in this paper with different propagation scenarios. The proposed adaptive scheme was implemented based on a distributed cooperative relay system (DCRS) in the communication network.

II. DISTRIBUTED COOPERATIVE RELAY STATIONS WITH IDEAL RELAY-TO-DESTINATION CSIT
In this scenario, the base station transmitter has a perfect Source-Relay (S-R) CSIT and totally delayed source-destination CSIT, and the relay station transmitter has a perfect Relay-Destination (R-D) CSIT. In general, the main idea to implement the interference alignment scheme is to use a relay station to design the beamforming based on the perfect relay-destinations (R-D) CSIT assumption, and to make all the receivers see the same linear combination for interference signals. Assume that there are K users in the propagation system, and the length of symbols to the users is denoted as $L$, since the base station transmitter has the perfect S-R CSIT, the transmitter implements the SLNR linear precoding scheme so the K relay stations can achieve the desired signals. When the relay station listens to the channel, the received signals at $k^{th}$ relay station are denoted as:

$$y_{\text{relay-RU}}^{k} = h_{k}^{(S-R)}(\gamma)w_{\text{SLNR}}^{k}s_{k}^{'} + \sum_{j=1,j\neq k}^{K}h_{k}^{(S-R)}(\gamma)w_{\text{SLNR}}^{j}s_{j}^{'} + n_{k}^{'}$$

(1)

In above $h_{k}^{(S-R)}$ is the propagation channel matrix between base stations to $k^{th}$ relay station. $w_{\text{SLNR}}^{k}$ is the SLNR precoding matrices on the $k^{th}$ relay station’s desired signal $s_{k}^{'}$. The second term denotes the co-channel interference, and with the ideally SLNR precoding scheme this term will equal zero at the relay station receiver side. The third term is the additive white Gaussian noise. It should be noted that the base station only broadcasts the signals at the first propagation layer; before the relay station has finished the following interference alignment process, the base station will not begin
the next step propagation. Once the BS sends the signal at time slot $\gamma$ in the first layer transmission as the original MAT scheme, the receive signals for each user are denoted as the following equations:

$$y_j(\gamma) = h^{(S-D)}_k(\gamma) \sum_{j=1}^{K} R^{(j)}(\gamma)$$  \quad (2) \quad \text{and} \quad R^{(j)}(\gamma) = \sum_{l=1}^{L} w_j(\gamma) h_j^{(l)}(\gamma)$$  \quad (3)

In equation (3) $w_j$ is the S-R CSIT base SLNR precoding matrices and $L$ is the length of vector of the transmission symbols. Different from feedback to the CSI to the base station in the original MAT scheme or the STIA scheme in [4], the source-to-destination CSI will feedback from the receiver to the desired $k$th relay station. The source-to-destination CSI from user $k$ which feed backs to the relay station in time slot $\gamma$ is $\hat{h}_k(\gamma)$. Once the relay station achieves the CSI feedback from destinations, the relay control station will start to generate the beamforming matrices denoted as $M_{\text{relay}}(n)$, where

$$M_{\text{relay}}(n) = V_{ZF}(n)P(n)$$  \quad (4)$$

$V_{ZF}(n)$ is zero forcing beamforming matrices at time slot $n$, and $P(n)$ is the Relay interference alignment matrices at time slot $n$, where:

$$p_{i,j}^n = \frac{\hat{h}_i(\gamma) w_j(\gamma)}{h^{R-D}_{ik}(n)} (k \neq j)$$  \quad (5)

In equation (5), $h^{R-D}_{ik}(n)$ is the $n$ time slot R-D channel matrices. The matrices of (5) need to keep the diagonal of the matrices to 1, which means $\text{diag}(P(n)) = [1, \cdots, 1] \in \mathbb{C}^{K \times 1}$ (6). This will hold the current signal in time slot $n$, and achieve the time diversity to solve the vector in single antenna user equipment. Therefore the whole expression of $M_{\text{relay}}(n)$ is expressed as:

$$M_{\text{relay}}(n) = V_{ZF}(n)P(n) = \text{inv}(h(n)) \cdot \begin{bmatrix}
    h^{R-D}_{11}(n) & h^{R-D}_{12}(n) & \cdots & h^{R-D}_{1L}(n) \\
    h^{R-D}_{21}(n) & h^{R-D}_{22}(n) & \cdots & h^{R-D}_{2L}(n) \\
    \vdots & \vdots & \ddots & \vdots \\
    h^{R-D}_{L1}(n) & h^{R-D}_{L2}(n) & \cdots & h^{R-D}_{LL}(n)
\end{bmatrix}
\begin{bmatrix}
    \hat{h}_1(\gamma) & \hat{h}_2(\gamma) & \cdots & \hat{h}_L(\gamma) \\
    \hat{h}_2(\gamma) & \hat{h}_2(\gamma) & \cdots & \hat{h}_L(\gamma) \\
    \vdots & \vdots & \ddots & \vdots \\
    \hat{h}_L(\gamma) & \hat{h}_L(\gamma) & \cdots & \hat{h}_L(\gamma)
\end{bmatrix}
\begin{bmatrix}
    w_{1}^{\text{SLNC}}(\gamma) \\
    w_{2}^{\text{SLNC}}(\gamma) \\
    \vdots \\
    w_{L}^{\text{SLNC}}(\gamma)
\end{bmatrix}$$  \quad (7)

Then the received signal at $k$th user after $n$ time slot relay station propagation is:

$$y_{j}(n) = h^{R-D}_{ik}(n)M_{\text{relay}}(n) s_k = \sum_{j=1, j \neq k}^{K} \hat{h}_j(\gamma) R_j(\gamma) + h^{R-D}_{ik}(n) R_k(n + L - 1) + z_j(n)$$  \quad (8)

Assume that the length of desired symbol vector $L=K$, therefore $n+K-1$ time slots propagation is needed:

$$y(n + L - 1) = \sum_{j=1, j \neq k}^{K} \hat{h}_j(\gamma) R_j(\gamma) + h^{R-D}_{ik}(n + L - 1) R_k(n + L - 1) + z_j(n + L - 1)$$  \quad (9)

Then combined with (2) we can achieve:

$$y(n + L - 1) - y(\gamma) = h^{S-D}_{ik}(n + L - 1) R_k(n + L - 1) - h^{S-D}_{ik}(\gamma) R_k(\gamma) + z_j(n + L - 1) - z_j(\gamma)$$  \quad (10)

As the result, with this relay based space-time interference alignment, the achieved Degree of freedom is:

$$D = \frac{1}{K} \left( \frac{1}{1/K + 1} \right) = \frac{1}{1/K + 1}$$  \quad (11)

### III. DISTRIBUTED COOPERATIVE RELAY STATIONS WITH MIXED RELAY-TO-DESTINATION CSIT

In the previous case, the current CSIT always exists in Relay-Destination Channels, which means the entire mobile users move with a very slow velocity in the visible areas of the distributed relay system. However, sometimes the CSIT in Relay-Destination Channels may be the totally delayed CSIT; for example, some of the mobile users are moving with a high velocity or moving in the non-visible areas (NLoS). Let’s regard the R-D channels in the previous case as ‘ideal channels’ and regard the R-D channels with delayed CSIT as ‘non-ideal channels’. We defined the ratio between the ‘non-ideal channels’ and total R-D channels as $\rho$. For the case of $K$ multi-users, if the number of ‘non-ideal channels’ is $\alpha$, then we have:

$$\rho = \frac{\alpha}{K}$$  \quad (12)

Suppose that the transmission processing is started at time slot $\gamma$. In the first layer, similar with the MAT scheme, the base station transmits the $K$ users’ information in $K$ slots. Similar with the scheme in the ideal case in the last section, the base station only broadcasts the signals at the first propagation layer; before the relay station finished the following
interference alignment process, the base station will not begin the next step propagation. The received signal in the relay station is:

$$y_{\text{relay}}^k = H_{k,k}^{S-R} w_{\text{SLNR}}^k s^k + \sum_{j=1,j\neq k}^{K} H_{k,j}^{S-R} w_{\text{SLNR}}^j s^j + n_z$$  \hspace{1cm} (13)$$

For the ideal case, if the base station has the accurate CSIT to the distributed relay remote units, the second term is zero. After the first layer transmission, the distributed relay remote units ideally have already recognized the desired signal to the desired destination. Therefore, the following interference alignment process is moved from the base station to distributed relay stations. Since the base station absence the current CSIT to the multi-users, the received signals of each user are both include the desired signal and the overheard interference signals. The received signal in Kth users in time slot γ + δ is denoted as:

$$y_{\text{user}}^k (\gamma + \delta) = H_{k,k}^{S-D} (\gamma + \delta) w_{\text{SLNR}}^k s^k, \delta \in [1, K]$$  \hspace{1cm} (14)$$

Different from the completely pessimistic assumption in the original MAT scheme [1], an adaptive precoding scheme can be implemented in the distributed relay system, as stated at the beginning, since the relay system may probably be aware of some of the current CSIT. Without loss of generality, we assume that there are K multi-users with symbol vector length L=nK. Meanwhile from the standpoint of the relay system, the number of blind channels ('non-ideal channels') is α. Therefore after layer transmission, the received signals for K users in different time slots are shown in the form below:

<table>
<thead>
<tr>
<th>γ+1</th>
<th>γ+2</th>
<th>γ+3</th>
<th>...</th>
<th>γ+K</th>
</tr>
</thead>
<tbody>
<tr>
<td>(y_{\text{user}}^1 l)</td>
<td>(y_{\text{user}}^2 l)</td>
<td>(y_{\text{user}}^3 l)</td>
<td>(\ldots)</td>
<td>(y_{\text{user}}^K l)</td>
</tr>
</tbody>
</table>

Table 1 K User Received Signals in K time slots

In table 1:

$$L_k(s_k) = \sum_{l=1}^{L} H_{k,l}^{R-D} (\gamma + k) s^l_1$$  \hspace{1cm} (15)$$

$$I_k(s_j) = \sum_{l=1}^{L} H_{k,l}^{R-D} (\gamma + k) s^j_l$$  \hspace{1cm} (16)$$

Here we regard all the users with a ‘non-ideal channel’ as a virtual single user \(\nu\). Therefore, the number of users in the system now is \(J = K - \alpha + 1\). Since now the relay station has the ideal CSIT for the good users, so with decomposition-based precoding, the relay station can prevent the virtual \(\nu\) ‘s power from interfering with other users. Now define the ideal user’s channel matrices as:

$$\hat{H}_\nu = \begin{bmatrix} H_\nu^T, \cdots, H_{\nu-1}^T, H_{\nu+1}^T \cdots H_{K-\alpha+1}^T \end{bmatrix}$$  \hspace{1cm} (17)$$

With the idea of the channel decomposition based precoding scheme, the user \(\nu\) ‘s precoding matrices are restricted to be in the null space of \(K - \alpha\) user’s channels. Meanwhile, each one of the \(K - \alpha\) users’ (in ideal channels) precoding matrices will also restrict itself to be in the null space of other user channels, except the single virtual user. That means the good channel users will still leak the signal to the non-ideal channel users. As mentioned, before starting the second layer transmission, for the ideal case the interference to user \(K - \alpha\) will be canceled or be in alignment at the receiver side. In that case, in the following transmission layers, the user \(K - \alpha\) will achieve enough interference cleared signal to compute the desired signal in the next \(K - 1\) time slots. However, since the relay station has an absence of the current CSIT to user \(\nu\), there is no SVD based precoding to prevent the interference from \(K - \alpha\) users to \(\nu\). Therefore the desired signal for user \(K - \alpha\) will bring the interference to the ‘non-ideal channel’ users. In order to align the interference from user \(K - \alpha\), the overheard signals in time slots of the first layer in ‘bad channel users’, will be employed to align this type of interference. A detection matrix \(G_{K-\alpha}\) can be computed in the \(\alpha\) users’ receiver according to the overheard signals, denoted as:

$$G_{K-\alpha} (\gamma + l) = H_{k-\alpha}^{S-D} (\gamma + \alpha + l) H_{k-\alpha}^{S-D} (\gamma + \alpha + l)^{-1}, l \in [1, L]$$  \hspace{1cm} (18)$$

In the following L-1 time slots after the first layer MAT transmission, the received signals in user \(\alpha\) can align the interference caused by user \(K - \alpha\) as below:

$$y_{\text{user}}^{\alpha \text{MAT}} (l) = y_{\text{user}}^{\alpha} (l) - \sum_{k=\alpha+1}^{K} G_{\alpha} (\gamma + l) I_{\alpha} (s_{k-\alpha}), l \in [1, L]$$  \hspace{1cm} (19)$$
The output signal $y_{\text{MAT}}^\alpha(I)$ is equal to the MAT scheme, in which a system’s multiuser number is $K = \alpha$. Therefore in this way, we actually just implement the MAT scheme to $\alpha$ users, and implement the linear precoding scheme to $K - \alpha$ users. Different from the previous MAT scheme, the relay system can adaptively combine the MAT scheme and linear precoding scheme with different $\rho$ scenarios. That actually dynamically optimized the complexity of the MAT scheme with the awareness of the CSIT in the relay network.

The Degree of Freedom in this case is denoted as:

$$D_\text{DoF}(\frac{1}{K}) = \frac{1}{\left(\frac{1}{1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{\alpha}} + \frac{1}{K}(K-\alpha)\right)} = \frac{1}{\frac{2}{2} + \left(\frac{1}{1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{\alpha}} + \frac{1}{K}(K-\alpha)\right)} \cdot \frac{2 + \sum_{\omega=1}^{\rho} \frac{1}{\omega + 1} - \rho}{K}$$

(20)

The term $(K - \alpha)/K$ in the position of denominator in equation (20) denotes the extra time slots employed to re-transmit the combined signal to the receiver, so that the receiver can resolve the symbol which the vector length is. The essential final retransmission is to use the character of the variant propagation channel to achieve the diversity and the desired signal, whose vector length is $K$. The performance gain between relay based adaptive MAT scheme and classic MAT scheme in dB are plotted as below:

![Fig.1 DoF Gain between Relay Based Adaptive MAT and Original MAT](image)

IV. CONCLUSION

Generally, this paper proposes the different relay interference alignment schemes in different propagation scenarios in a single antenna multiuser system with delayed CSIT. By researching the different cases of propagation conditions, the function of Degree of Freedom is derived in different propagation scenarios; meanwhile we can conclude that: the distributed cooperative relays can help to improve the DoF even if the delayed CSI exists between the relay and destination. In some scenarios when combined with the MAT and linear precoding method, even if some of the source-relay link is weak, it only causes a small effect to the Degree of Freedom. The Distributed Cooperative Relay System can separate precoding jobs, so that it can largely simplify the complexity of the precoding scheme in the Base Station.

REFERENCES