OFDM Cooperative Relay Transmission and Interference Elimination Technology

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Abstract. Aiming at Orthogonal Frequency Division Multiplexing (OFDM) cooperative relay transmission system, a scheme of interference elimination between OFDM relays based on precoding was proposed for OFDM system continuous relay network. The new scheme precodes the frequency domain signals of the source nodes alternately, maps the expected signals and interference signals of the relay to two orthogonal subspaces. The interference elimination of the relay is achieved and the expression of the optimal precoding matrix is deduced. The application in OFDM system can effectively eliminate the influence of multipath effect on system performance. The effectiveness of the scheme is verified by simulation experiments. Keywords—Cooperative relay; OFDM channel; interference elimination

1. Introduction
OFDM has been widely studied by researchers for its efficient spectrum utilization and ability to resist multipath fading. The core idea of OFDM technology is to spread the data on multiple orthogonal subcarriers for transmission, thus reducing the symbol rate on each subcarrier and making the bandwidth of each subcarrier less than the coherent bandwidth. Therefore, it can be considered that all frequencies experience the same fading, which is flat fading. At the same time, because OFDM can allow multiple sub-carriers to be aliased, its spectrum efficiency has been greatly improved. Applying the typical application of virtual full-duplex relay to OFDM, the dual-path continuous relay system can not only improve the transmission rate but also improve the frequency efficiency and resist the frequency diversity caused by the multipath effect. At present, there are few studies on interference elimination of dual-path continuous relay in OFDM. In the single-antenna transceiver model, since there are no redundant antennas to construct the null space, the main interference elimination scheme is still based on the channel information interference subtraction scheme. The scheme based on channel information first needs to obtain channel information through channel estimation, and then subtract the estimated IRI signal from the relay, so as to achieve the purpose of interference elimination. Channel estimation at the relay exit will consume a lot of system resources and increase the processing burden of the relay. Moreover, in the actual situation, estimation error is inevitable in the channel estimation, which will lead to incomplete elimination of IRI signal, residual IRI and cumulative noise, and ultimately affect system performance.

Aiming at the problem of traditional interference elimination between relays, the precoding interference elimination scheme is applied to the dual-path continuous relay network in the OFDM system, and the single antenna relay model in the quasi-static frequency selective fading channel is studied.

2. System model design
Consider an AF dual-path continuous relay network using block transmission in an OFDM system,
which is composed of one source node $S$, two relay nodes $R_1, R_2$ and one destination node $D$. Due to the large path loss between the source node $S$ and the destination node $D$, the data cannot be transmitted. That is, there is no direct link. The signal transmission of the system can be divided into two time slots. In odd time slot, the source node $S$ sends the source signal to the relay $R_1$, and the relay $R_2$ sends the signal to the relay $R_1$ and the destination node $D$; in even time slot, the source node $S$ sends the source signal to the relay $R_2$, and the relay $R_1$ sends the signal to the relay $R_2$ and destination node $D$.

2.1. System model design

In this section, the dual-path continuous relay system model based on precoding in the OFDM system adopts the precoding interference elimination scheme based on row space mapping, which requires precoding of the data in the frequency domain and corresponding encoding and decoding operations at each node. In order to precode the source data matrix, this section designs two precoding matrices $P_i \in \mathbb{C}^{K \times M}$ and $Q_i \in \mathbb{C}^{K \times M}$, which precode the source data matrix $P_i$ by multiplying the right times the precoding matrix $D_i$ in odd time slot and the source frequency data matrix $P_i$ by multiplying the right times the precoding matrix $D_i$ in even time slot.

After precoding the source frequency domain data matrix, the RF domain matrix to be issued can be expressed as:

$$X'_i = D_i P_i \in \mathbb{C}^{N \times M}$$  (1)

Where, the precoding matrix is the row full rank orthogonal matrix $P_i \in \{1, 2\}$. In order to ensure that the average power of source data before and after precoding remains unchanged, the precoding matrix has the following properties:

$$\text{tr}\{P_i P_i^H\} = M$$  (2)

At the source node, the average power of the frequency domain data precoded can be expressed as:

$$\sigma_s^2 = \text{tr}[(X'_i X'_i^H - \sigma_s^2 I_M) / N_M]$$  (3)

Where $\sigma_s^2$ represents the average power of the data matrix before the precoding, and $\sigma'_s$ represents the average power of the data matrix after the precoding.

Before launching, the frequency domain data matrix needs to pass through IFFT to transform it into the time domain. The details are as follows:

$$X'_i = F^T X'_i = F^T D_i P_i$$  (4)

In order to prevent IBI, it is necessary to insert CP of appropriate length, remove CP after the relay receives the corresponding signal, and get the relay node to receive the signal. The time $l$ domain signal received by the relay $R_i$ at the first slot is as follows:

$$Y'_i = H_{SR} X'_i + H_{R_i R_i} X'_i + W'_i, \quad H_{SR} = H_{SR}^T \quad H_{R_i R_i} = H_{R_i R_i}^T$$  (5)

Among them, additive gaussian white noise $W'_i \in \mathbb{C}^{N \times M}$ is obeyed $\mathcal{CN}(0, \sigma'_s^2)$.

Carry $Y'_i$ on FFT, transform it to frequency domain, get frequency domain signal $\tilde{Y}_i$.

$$\tilde{Y}_i = F Y'_i = F H_{SR} F^T D_i P_i + F H_{R_i R_i} X'_i + F W'_i$$  (6)

Firstly, the decoding matrix $Q_i \in \mathbb{C}^{M \times K}$ is used for decoding $\tilde{Y}_i$, and then the precoding matrix $P_i$ is used for reencoding operation. Finally, the normalized operation is performed on the signal. The frequency domain signal to be sent by the time $l+1$ slot relay $R_i$ can be obtained as follows:

$$X'^{l+1} = \beta'_i (F H_{SR} F^T D_i P_i + F H_{R_i R_i} X'_i + F W'_i) Q_i P_i$$  (7)

Where $\beta'_i$ is the relay amplification factor.
The signal $\tilde{X}_{R_i}^{l+1}$ is transformed by IFFT, and the time domain signal is obtained as follows:

$$X_{R_i}^{l+1} = F^l \tilde{X}_{R_i}^{l+1} \tag{8}$$

At the first slot $l+1$, the destination node $D$ receives the time-domain signal from the relay $R_i$, which can be expressed as:

$$Y_{D}^{l+1} = H_{R_i, D}^{l+1} X_{R_i}^{l+1} + W_{D}^{l+1} \tag{9}$$

Among them, additive gaussian white noise $W_{D}^{l+1} \in \mathbb{C}^{N_x, M}$ is obeyed $\mathcal{CN}(0, \sigma_{w, d}^2)$.

Then, FFT transformation was performed on the target point to receive the time- domain signal, and the final frequency- domain signal was obtained as follows:

$$\tilde{Y}_{D}^{l+1} = F Y_{D}^{l+1} = F H_{R_i, D}^{l+1} X_{R_i}^{l+1} + F W_{D}^{l+1} \tag{10}$$

2.2. Pre-coding interference elimination

In the dual-path continuous relay net- work of OFDM system, two relays are sent and received alternately, so it is inevitable to bring interrelay interference. Interrelay interference and relay noise transmission and transmission back and forth will seriously affect the performance of the system, so it is necessary to eliminate interrelay inter- ference. In the traditional OFDM single- antenna dual-path continuous relay network, the most commonly used interference elimination method is still based on channel state information interference elimination, that is, CSI is obtained through channel estimation, and then the interference information is subtracted at the relay, so as to achieve the purpose of interference elimination. This requires the relay to perform channel estimation to obtain CSI, thus increasing the relay processing burden and resource overhead. When there is estimation error in the channel estimation, the system will also produce residual IRI and cumulative noise, which will have a serious impact on the system performance. The following precoding interference elimination scheme can effectively avoid the above two problems, see below for details.

At the relay $R_i$, the frequency domain signal $\tilde{Y}_{R_i}^l$ is decoded by right multiplication of the decoder matrix $Q_i$, and the decoded signal is obtained:

$$\hat{Y}_{R_i}^l = \tilde{Y}_{R_i}^l Q_i$$

$$= F H_{S, R_i}^{l} F^l \tilde{D}_{S}^l P_i Q_i + F H_{R_i, R_i}^{l} X_{R_i}^l Q_i + F W_{R_i}^l Q_i$$

$$= F H_{S, R_i}^{l} F^l \tilde{D}_{S}^l + F H_{R_i, R_i}^{l} X_{R_i}^l Q_i + F W_{R_i}^l Q_i \tag{11}$$

Where, the decoding matrix $Q_i$ satisfies the following properties:

$$P_i Q_i = I_K \tag{12}$$

Then, the right multiplication precoding matrix $\hat{Y}_{R_i}^l$ is recoded $P_i$ and power normal- ization is carried out, $\tilde{X}_{R_i}^{l+1}$ can be expressed as:

$$\tilde{X}_{R_i}^{l+1} = \beta_i^{l} \hat{Y}_{R_i}^l P_i \tag{13}$$

Where, $\beta_i^{l}$ is the amplification factor of relay $R_i$, specifically defined as:

$$\beta_i^{l} = \frac{P_{S}}{\sqrt{P_{S} \left| H_{S, R_i}^{l} \right|^2 + \sigma_{s, r}^2}} \tag{14}$$

Where, $P_S$ and $P_{R_i}$ are respectively source node transmit power and relay $R_i$ transmit power.

In the first time slot ($l=1$), the relay $R_i$ only receives signals from the source node $S$ without interference from the relay, so the first time slot $R_i$ in the received signal frequency domain can be expressed as:

$$\hat{Y}_{R_i}^l = F H_{S, R_i}^{l} F^l \tilde{D}_{S}^l P_i + F W_{R_i}^l \tag{15}$$

According to formula (7), the transmitted signal $R_i$ in time domain at the second time slot ($l=2$)
can be expressed as:
\[ X_{R_2}^2 = \beta_i^H H_{sr}^i \tilde{F}^H \tilde{D}_g^i \mathbf{P} + \beta_i^H W_{R_2}^i \mathbf{P} \]  
(16)

According to formula (11), the decoded signal \( R_2 \) in the second slot (\( l = 2 \)) is:
\[
\hat{Y}_{R_i}^2 = \mathbf{F} \mathbf{H}_{sr}^i \mathbf{F}^H \mathbf{D}_g^i + \mathbf{F} \mathbf{W}_{R_2}^i \mathbf{Q}.
\]  
(17)

As can be seen from equation (17), \( \hat{Y}_{R_i}^2 \) contains useful signals sent by the source node as well as interference signals from the relay \( R_1 \). In order to eliminate relay interference, the following definition is made:
\[ \mathbf{P}^i \mathbf{Q} = \mathbf{0}_{K} \]  
(18)

That is, the decoding matrix \( \mathbf{Q} \) belongs to the null space of the precoding matrix \( \mathbf{P} \). Equation (17) can be transformed into:
\[
\hat{Y}_{R_i}^2 = \mathbf{F} \mathbf{H}_{sr}^i \mathbf{F}^H \mathbf{D}_g^i + \mathbf{F} \mathbf{W}_{R_2}^i \mathbf{Q}.
\]  
(19)

According to equation (8) and the third time slot (\( l = 3 \)), the time domain signal \( R_2 \) sent is:
\[
X_{R_i}^3 = \beta_i^H H_{sr}^i \mathbf{F}^H \tilde{D}_g^i + \beta_i^H W_{R_2}^i \mathbf{Q}.
\]  
(20)

By substituting equation (20) into equation (11), we can get the recursive expression after decoding the received signal in the slot \( l \) relay \( R_i \) as follows:
\[
\hat{Y}_{R_i}^l = \mathbf{F} \mathbf{H}_{sr}^i \mathbf{F}^H \mathbf{D}_g^i + \mathbf{F} \mathbf{W}_{R_2}^i \mathbf{Q}.
\]  
(21)

Accordinly, the time domain signal \( R_i \) emitted at the first slot \( l + 1 \) can be expressed as:
\[
X_{R_i}^{l+1} = \beta_i^H H_{sr}^i \mathbf{F}^H \mathbf{D}_g^i \mathbf{P} + \beta_i^H W_{R_2}^i \mathbf{Q} \mathbf{P}.
\]  
(22)

It can be seen from equation (22) that the precoded interference elimination scheme can completely eliminate the IRI signal and inter-relay noise in the dual-path continuous relay network of OFDM system under the condition of unknown CSI. At the same time, the interference elimination between relays is not affected by the channel estimation error.

3. Pre-coding design

After the relay interference is eliminated, equation (11) can be rewritten as:
\[
\hat{Y}_{R_i}^l = \beta_i^H H_{sr}^i \mathbf{F}^H \mathbf{D}_g^i + \beta_i^H W_{R_2}^i \mathbf{Q}.
\]  
(23)

In the following, the maximum SNR criterion is adopted to maximize the effective SNR of the received signal in equation (23) to achieve the optimal design of the precoding matrix. In order to facilitate derivation, time slot superscript is ignored and effective SNR is defined as:
\[
\text{SNR}_{\text{eff}} = \frac{E[\| \beta_i^H H_{sr}^i \mathbf{F}^H \mathbf{D}_g^i \|^2]}{E[\| (\beta_i^H H_{sr}^i \mathbf{F}^H \mathbf{D}_g^i + \mathbf{F} \mathbf{W}_{R_2}^i) \mathbf{Q} \|^2]}.
\]  
(24)

The problem of designing the optimal decoding matrix \( \mathbf{Q} \) to maximize the effective SNR can be equivalent to designing the optimal precoding matrix \( \mathbf{P} \) to maximize the effective SNR. Specific include:
\[
\max_{\mathbf{P}, \mathbf{Q}} \text{SNR}_{\text{eff}}
\]  
\[ \text{s.t.} \quad \text{tr}\{\mathbf{P}\mathbf{P}^H\} = M, \quad i \in \{1, 2\} \]  
(25)

Combining equations (24) and (25), it is not difficult to see that the problem of maximizing effective SNR can be simplified to the problem of minimizing non-gaussian composite noise \( E[\| (\beta_i^H H_{sr}^i \mathbf{W}_{R_2}^i + \mathbf{F} \mathbf{W}_{R_2}^i) \mathbf{Q} \|^2] \), which can be expressed as:
\[ E[\| (\beta F h_k w_n + \text{FW}_n)^i \|] = \text{tr} \{ E[(\beta F h_k w_n + \text{FW}_n)QQ^T(\beta F h_k w_n + \text{FW}_n)^i] \} = N(\beta^2 \sigma^2_k \sigma^2_n + \sigma^2_r) \text{tr} \{ QQ^T \} = N(\beta^2 \sigma^2_k \sigma^2_n + \sigma^2_r) \text{tr} \{ (P P^H)^{-1} \} \]

The optimal precoding and decoding matrix \( O = [o_\omega, o_\omega, \ldots, o_{M-1}] \in C^{M \times M} \) can be designed through any orthogonal matrix (such as DFT matrix, multiphase sequence matrix, Chirp matrix and Walsh-Hadamard matrix). The specific properties are as follows:

\[ R_{ij}(r) = \sum_{n=0}^{N-1} m(n) o_{\omega}^i (n + r) = \begin{cases} 1, & r = 0, i = j \\ 0, & 0 < r < M, i = j \\ 0, & 0 < r < M, i \neq j \end{cases} \]

4. Experimental simulation and performance analysis

In this section, aiming at the single-antenna AF dual-path continuous relay network in OFDM system, the scheme of relay interference elimination based on channel state information and the scheme of relay interference elimination based on precoding are simulated, and the performance of each scheme is analyzed mainly from the perspective of BER performance.

The channels of the single-antenna AF dual-path continuous relay network in the OFDM system are set as mutually independent frequency-selective Rayleigh block fading channels, that is, the channels do not change in the same time slot. The source data adopts QPSK modulation signal and the data length is \( L = 256 \). In the simulation experiment, it is assumed that the average transmission power of the source node and the two relay nodes is set as \( P_1 = P_2 = P_3 = 1 \), \( \sigma^2_k = \sigma^2_n = \sigma^2_r \), the orthogonal matrix is set as Walsh-Hadamard matrix \( O \), and the size of the precoding matrix \( P_1 \) and \( P_2 \) is \( M = 32 \).

Assuming that the channel estimation performance of all single-hop channels is the same, the channel estimation error of different links is set as a multiplexing Gaussian random variable. The estimated error is expressed by the ratio of the estimated error signal power to the total received signal power \( \omega \) (dB). The parameter corresponding to the perfect CSI is \( \omega = -\infty \), the ratio of the estimated error signal power to the total received signal power.

Figure 1 compares the bit error performance of the precoding scheme with that of the continuous relay network with no relay link under different estimation errors. Since there is no IRI in the continuous relay network of the unrepeatable link, this situation can be considered as the upper limit of the performance of the continuous relay network. From figure 1 we can see, under the condition of all kinds of error, the ber performance of precoding scheme and WuZhongJi link completely overlap, it shows that the proposed precoding scheme in this paper can eliminate the IRI and cumulative noise completely, thus the system model of equivalent in the case of WuZhongJi link can be further simplified as two parallel single relay coordination network.

![Figure 1](image-url)

Figure 1. The error curve of the precoding scheme and the continuous relay network with no relay link under different estimation errors
Figure 2 shows the performance comparison between the precoded interference elimination scheme and the traditional channel-based estimation interference elimination scheme under various estimation errors. It can be seen that under the same estimation error, the error performance of the precoding scheme is better than that of the traditional scheme based on channel estimation. This is because the pre-encoded interference elimination scheme can completely eliminate IRI and cumulative noise, while the traditional scheme is affected by the estimation error, and the relay interference signal elimination is incomplete, with residual IRI and cumulative noise. By figure 2 as you can see, no error of estimate (\( \omega = -\infty \)), when the precoding scheme performance is slightly better than the traditional scheme, this is due to the traditional scheme in the absence of estimation error after can completely eliminate the interference signal and relay to eliminate noise but couldn't get to end, and the precoding scheme to relay link completely cut off, so the precoding performance slightly better than that of the conventional scheme \( \omega = -\infty \).

![Figure 2](image)

Figure 2. The performance curves of the precoded interference elimination scheme and the traditional channel estimation-based interference elimination scheme under various estimation errors

5. Chapter summary
In this paper, a blind relay interference elimination scheme based on precoding is proposed for the interrelay interference in the virtual full-duplex network in OFDM systems. By alternately precoding the signal, the signal is mapped to the orthogonal subspace independent of channel information, and the corresponding decoding matrix is multiplied by the right at the relay, so as to completely eliminate IRI and cumulative noise in the case of unknown channel information. Simulation results show that the proposed scheme can effectively cut off the relay link and its performance is superior to the traditional scheme based on channel information. This scheme avoids the extra overhead of acquiring channel information in the relay and eliminates the influence of channel estimation error on interference cancellation performance. Since the scheme does not rely on channel information, it has certain practical application value, especially for small relay networks that cannot use excessive resource overhead and complex algorithms to obtain channel information.

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