Abstract— In an OFDM-based cooperative relay system, the arrival times and carrier frequency offsets (CFOs) of the signals from different relays are most likely different. Estimation of these timing offsets and CFOs is a crucial and challenging task. In this paper, a new preamble structure is designed, and an efficient time and frequency offset estimator is proposed for the OFDM-based cooperative system. The signals from different relays are separated using the low cross-correlated pseudo noise (PN) sequences. The coarse timing synchronization is accomplished using the time-domain symmetric conjugate of the preamble, and the fine timing synchronization is accomplished by segmented moving correlation using the good autocorrelation feature of the preamble in the time domain. The fractional frequency offset is estimated using the phase difference of the two duplicated training symbols, and the integral frequency offset is estimated by utilizing the low energy at null subcarriers and the good autocorrelation features of the preamble in the frequency domain. The analysis and the simulation results show that adopting the proposed preamble structure and synchronization algorithms, the destination can estimate not only the timing offsets from all relays but also the frequency offsets from all relays.

Keywords-Cooperative systems; OFDM; Preamble; Time synchronization; Frequency synchronization

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has attracted a lot of attentions for being able to achieve higher spectral efficiencies. The cooperative approach has also gained some interests because it can exploit space diversity to combat channel fading and improve system performance in multi-path environments. The combination of OFDM and cooperation can provide high spectral efficiency and robustness against channel fading and is a very promising approach for future broadband mobile communication systems.

As the performances of OFDM-based cooperative systems are very sensitive to symbol timing offset and carrier frequency offset (CFO), time-frequency synchronization is a hot research topic. For the classical two-phase cooperative relay system, the synchronization is divided into the synchronization from source to relays and the synchronization from relays to destination. The former is straightforward since it is similar to the synchronization for point-to-point OFDM systems [1]-[3], in which the transmitted signal simultaneously arrived in the receiver and the receiver only need to resolve one CFO and timing acquisition. On the contrary, the latter is very challenging because relays are distributed in different locations and the arriving times and frequency offsets of the transmitted signals from different relays are different, just like in the distributed MIMO systems. A lot of research work has been devoted to solving the synchronization problem of the MIMO-OFDM system [5]-[10], however most of them focus on the synchronization in centralized MIMO-OFDM systems [5]-[9] and hence are not applicable for the synchronization from relays to the destination in cooperative systems. [10] discusses the time synchronization of the distributed MIMO-OFDM system, which can be applied in the time synchronization from relays to destination in the cooperative system, but the frequency synchronization is not studied.

In this paper, a new training structure is designed and an efficient time and frequency offset estimator is proposed for the OFDM-based cooperative system. In the proposed approach, The signals from different relays are separated using the low cross-correlated pseudo noise (PN) sequences. The coarse timing synchronization is accomplished using the time-domain symmetric conjugate of the preamble, and the fine timing synchronization is accomplished by segmented moving correlation using the good autocorrelation feature of the preamble in the time domain. The fractional frequency offset is estimated using the phase difference of the two duplicated training symbols, and the integral frequency offset is estimated by utilizing the low energy at null subcarriers and the good autocorrelation features of the preamble in the frequency domain. The simulation results show that, compared with the estimator in [10], the proposed estimator has a significantly smaller mean square error (MSE) of the timing offset estimation. In addition, it is remarkable that the proposed approach can simultaneously estimate the frequency offsets from all relays to the destination.

The rest of this paper is organized as follows. In Section II, the signal model of cooperative systems is provided. Section III presents the proposed training structure and the corresponding time and frequency offset estimation algorithms for the OFDM-based cooperative system. The performance of the proposed estimator is investigated and compared to that of the estimator in [10] by computer simulation in Section IV. Finally, some conclusion remarks are made in Section V.

II. SIGNAL MODEL

Consider the classical two-phase cooperative relay system with m relay nodes shown as Fig. 1. Suppose every
node is installed with single antenna. In phase one, the source node sends symbols to all relay nodes. After some processes in each relay node, the sum of signals transmitted by m relay nodes is received in the destination during the second phase. Note that the synchronization during the first phase is much easier than that in the second phase. Thus, we consider only the synchronization problem between the relay nodes and the destination node here.

III. TIME AND FREQUENCY OFFSET ESTIMATION IN OFDM-BASED COOPERATIVE SYSTEMS

A. Proposed Training Symbol

The proposed training structure for the OFDM-based cooperative systems is presented in Fig.2. The duplication of training symbol (TS) will be used for fractional frequency offset estimation. The training symbols in the frequency domain are m pseudo noise (PN) sequences with low cross-correlations for the m relays. The low cross-correlation property of the PN sequence is used to separate the signals from different relays. The large auto-correlation property of the PN sequences will be used for the fine timing estimation.

For the ith relay, i=1,2,...,m, the preamble in the frequency domain is designed to be of the form

\[ C_{i,preamble} = [0, \cdots, 0, C_{i,1}, C_{i,2}, \cdots, C_{i,K}, 0, \cdots, 0] \]

where \( C_{i,j} \) is a PN sequence, the values of \( j \) are +1 or −1, and \( K \) is the length of the PN sequence. The nulls in (3) will be used for integral frequency offset estimation. The corresponding time-domain complex baseband training symbol samples for the ith relay are assumed to be

\[ e_{i,preamble} = [c_{i,0}, c_{i,1}, \cdots, c_{i,N-1}] \]

where \( c_{i,j} \) and \( j \) are real

\[ c_{i,k} = c_{i,N-k}^* \quad k = 0, \cdots, N/2 \] (5)

The designed training symbol in the time domain can be represented as follows:

\[ e_{i,preamble} = [A_i, B_i] \]

where \( A_i \) represents samples of length N/2, and \( B_i \) is symmetric with the conjugate of \( A_i \). The symmetric conjugate property will be used for coarse timing estimation.
B. Timing Offset Estimation

1) Coarse time acquisition

In the proposed training structure, the sequence TS is repeated as shown in Fig. 2. With the special design in (3) leading to (6), the training structure of the proposed preamble in the time domain for \(i\)th relay is shown in Fig. 3. It is noted that \(A_{1i}=A_{2i}=A_{i}\), \(B_{1i}=B_{2i}=B_{i}\), and \(B_{2i}\) is symmetric with the conjugate of \(A_{2i}\). To ensure the timing metric has a single peak, only \(A_{1i}\) and \(B_{2i}\) are chosen for performing correlation. Then the timing metric can be defined as follows:

\[
M(n) = \left| \frac{p(n)}{R(n)} \right|^2
\]

where

\[
p(n) = \sum_{k=1}^{N/2-1} r(n+k) \cdot r(n+2N-k)
\]

\[
R(n) = \sum_{k=1}^{N/2-1} |r(n+k)|^2
\]

and the starting time of the preamble is approximated as

\[
\hat{\epsilon}_c = \arg \max_n (M(n))
\]

2) Fine time synchronization

Once the approximate timing position is detected, the fine time synchronization can be performed to determine the exact starting position for the packet from the \(i\)th relay by cross-correlate the received samples with the transmitted sequence of relay \(i\). The cross-correlation metric for relay \(i\) can be given by:

\[
\Phi_i(d) = \sum_{n=1}^{N_i} \sum_{k=1}^{V} r(\hat{\epsilon}_c + d + (n-1) \cdot V + k) \cdot c_{i,(n-1) \cdot V + k}
\]

\(d \in \Omega\)

where \(\Omega\) is the selected interval of \(d\), \(N_V\) is the number of selected blocks, \(V\) is the number of selected samples for performing the partial correlation and \(N_V \cdot V \leq N\). The fine timing synchronization for relay \(i\) is performed as:

\[
\hat{\epsilon}_{i,f} = \arg \max_d (\Phi_i(d))
\]

Thus the final estimation of timing offset for the \(i\)th relay is

\[
\hat{\epsilon}_i = \hat{\epsilon}_c + \hat{\epsilon}_{i,f}
\]

C. Frequency Offset Estimation

1) Fractional frequency offset estimation

After the time synchronization, using the two duplicated TS’s in Fig. 3, the fractional frequency offset for the \(i\)th relay can be estimated by

\[
\hat{f}_{i,\text{fine}} = \text{angle}\left\{ \frac{\sum_{k=1}^{\epsilon} r(\hat{\epsilon}_i + k) \cdot r(\hat{\epsilon}_i + k + N)}{2\pi} \right\}
\]

Notice that, due to the periodicity of \(2\pi\) of the \text{angle}(\cdot) function, the estimation range of the fractional frequency offset is within \((-0.5, +0.5)\). To improve the performance of the estimation accuracy of the fractional frequency offset, averaging over several estimated values can be used.

2) Integral frequency offset estimation

The estimation of the integral frequency offset for the \(i\)th relay can be divided into two steps: the coarse estimate and the fine estimate.

a) Coarse estimate by minimum energy detection

Since the proposed training symbol in the frequency domain contains null parts whose energy is very small in comparison with that of data when SNR is high, the end point of null part, \(N_{i,e}\), can be obtained by

\[
N_{i,e} = \arg \min_d \left\{ \sum_{k=0}^{\epsilon-1} \left| \hat{Z}_{i,(d-k)} \right|^2 \right\}
\]

where \(\hat{Z}_{i,k}, k = 0, 1, 2, \ldots, N-1\) is derived through FFT of the received training symbol with \(\hat{\epsilon}_i\) as the starting time sample of the FFT window, \(T = n_f + n_h\), \(d\) is the amount of estimated integral frequency shift and \((\bullet)_N\) is the modulo-\(N\) operator. Due to noise and fading channel environments, the location of end point for null part may have error.

b) Fine estimate by partial correlation

To reduce the error of coarse estimate, correlation of several samples around null part is used. It is obtained by

\[
N_{i}\epsilon = \arg \max_{d,w} \left\{ \sum_{n=1}^{N_w} \sum_{w=d}^{\epsilon} (\hat{Z}_{i,N_f+(n-1)\cdot W+w}) \cdot c_{i,(w-1)\cdot W+w} \right\}
\]

where \(d\) is the amount of estimated integral frequency shift, \(D\) is the selected interval of \(d\), \(N_W\) is the number of...
selected blocks, \( W \) is the number of samples selected for performing partial correlation, and \( N_{w} \cdot W \leq K / 2 \).

Therefore the estimation of integral frequency offset for relay \( i \) would be
\[
\hat{f}_{i,\text{int}} = N_{i,c} + N_{i,c} - (K / 2 + n_{i} / 2) \quad (17)
\]

To improve the performance of estimation, the two identical training symbols could be used for integral frequency offset estimation. The estimation of the total frequency offset for relay \( i \) would be
\[
\hat{f}_{i} = \hat{f}_{i,\text{int}} + \hat{f}_{i,\text{fine}} \quad (18)
\]

### IV. SIMULATION RESULTS

In this section, the performance of the proposed estimator is demonstrated. The performance of the estimator in [10] will also be studied and used as a benchmark.

#### A. Simulation Parameters

The proposed time and frequency offset estimation algorithm is investigated using the Monte-Carlo simulation method in a multipath fading channel. The channel consists of seven paths which have uniformly distributed delays over the interval of 0-30 µs. The multipath intensity profile is assumed to be \( \phi(\tau) \sim e^{-\tau/\tau_{rms}} \), where \( \tau_{rms} \) is 7µs. We assume the OFDM system has 2048 subcarriers with a 1kHz inter-carriers spacing. The length of CP is 128 samples. For simplicity, two relays are used in the OFDM-based cooperative system. The delays of the two relays are 0µs and 5µs, respectively and the normalized frequency offsets of the two relays are 4.3 and 2.9 subcarrier spacing, respectively. The proposed estimator applies \( V = 20, N_{F} = 6, W = 4, N_{w} = 40 \), the estimator in [10] applies \( L_{sp} = 512, L_{ap}^{2} = 511 \).

#### B. Timing Offset Estimation Performance

The mean error and the mean square error (MSE) reflects the bias and the variance of the estimation. Therefore, the performance of the proposed estimator is evaluated by the mean error and the mean square error, and compared with those of the estimator in [10]. TABLE I and TABLE II show the mean error and mean square error (MSE) of the timing offset estimation adopting the estimator in [10] and the proposed estimator respectively under multipath fading channels. It can be seen that, when the frequency offsets between the destination and the two relays are different, they can still be estimated accurately. It is noted that only the frequency synchronization performance of the proposed estimator is given here because the frequency synchronization is not studied in [10].

#### C. Frequency Offset Estimation Performance

Fig.4 and Fig.5 show the mean square error (MSE) of the frequency offset estimation adopting the proposed estimator under multipath fading channels. It can be seen that, when the frequency offsets between the destination and the two relays are different, they can still be estimated accurately. It is noted that only the frequency synchronization performance of the proposed estimator is given here because the frequency synchronization is not studied in [10].

![Fig.4 MSE of the frequency offset estimation for relay 1](image1)

![Fig.5 MSE of the frequency offset estimation for relay 2](image2)

### TABLE I PERFORMANCE OF TIME SYNCHRONIZATION FOR [10]

<table>
<thead>
<tr>
<th>SNR (dB)</th>
<th>Relay 1</th>
<th>Relay2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>MSE</td>
</tr>
<tr>
<td>1</td>
<td>8.66</td>
<td>1.32×10²</td>
</tr>
<tr>
<td>3</td>
<td>7.65</td>
<td>8.62×10¹</td>
</tr>
<tr>
<td>5</td>
<td>6.41</td>
<td>7.83×10¹</td>
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<tr>
<td>7</td>
<td>5.37</td>
<td>6.54×10¹</td>
</tr>
<tr>
<td>9</td>
<td>4.31</td>
<td>5.47×10¹</td>
</tr>
<tr>
<td>11</td>
<td>3.27</td>
<td>4.12×10¹</td>
</tr>
</tbody>
</table>

### TABLE II PERFORMANCE OF TIME SYNCHRONIZATION USING THE PROPOSED SCHEME

<table>
<thead>
<tr>
<th>SNR (dB)</th>
<th>Relay 1</th>
<th>Relay2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>MSE</td>
</tr>
<tr>
<td>1</td>
<td>0.041</td>
<td>1.72</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
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</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
The simulation results make it clear that the proposed scheme performs much better than the scheme in [10], therefore it is a favorable option for the time and frequency synchronization of OFDM-based cooperative systems.

V. CONCLUSION

In this contribution, the estimation of time and frequency offset was studied for the OFDM-based cooperative systems. A new training structure is designed and the synchronization has been accomplished by coarse time acquisition, fine time acquisition, fractional CFO estimation and integral CFO estimation. The simulation results show that, compared with the estimator in [10], the proposed estimator has a significantly smaller mean square error (MSE) of the timing offset estimation. In addition, it is remarkable that the proposed approach can simultaneously estimate accurately the frequency offsets from all relays to the destination.

REFERENCES


