Timing and Frequency Synchronization for Cooperative Relay Networks

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***Abstract*—This paper deals with timing and frequency synchronization in multi-relay cooperative networks operating with both large and small carrier frequency offset (CFO) over frequency-selective channels. A novel preamble based on constant amplitude zero auto-correlation (CAZAC) sequence is proposed, and a corresponding practical multistage scheme is presented. Joint timing and integral frequency synchronization is involved to resist multi-relay interference (MRI). Then, fractional frequency estimation is carried out, and fine timing estimation completes the synchronization scheme. The performance is evaluated in terms of the mean square error (MSE). Simulation results show that the method is robust under both flat-fading and multipath fading channels, and provides accurate estimation results in the presence of both large and small multiple CFO values.**

I. Introduction

Collaborative communication systems have recently attracted vast research attention due to their capability of increasing data throughput and robustness to signal fading in wireless networks [1]. It has been pointed out that with proper cooperative strategies, the same benefits of multiple-input-multiple-output (MIMO) systems can be achieved in cooperative systems with only one antenna at each node. However, much of the research done in this area assume perfect synchronization in the receiver, which is very difficult to achieve due to the spatial distributed nature of relays.

The spatial separation of relay nodes give rise to multiple timing offsets (MTOs) and different oscillator of each node with Doppler shift results in multiple carrier frequency offsets (MCFOs). The performance of relay network deteriorates severely when the synchronization errors are large. Thus, accurate estimation of MTOs and MCFOs is necessary to the successful deployments of cooperative relay networks. Joint estimation of MTOs, MCFOs is a very difficult problem because the signals from different transmitters are overlapped with each other at the destination. Moreover, the existing of MTOs and MCFOs will destroy the orthogonality between preambles or training sequences since these offsets are usually unknown at the transmitters. As a result, multi-relay interference (MRI) will occur at the destination which degrades the performance of estimators.

Existing joint estimator of MTOs, MCFOs can be categorized into two principal classes: 1) maximum-likelihood estimators (MLE) such as [2]–[4], where usually require exhaustive search and perform poorly when the parameters are close to one another; 2) correlation-based estimators (CBE), where utilize the correlation between the received signal and local sequences at the destination. However, the CBEs such as [5], [6] suffer from an error floor, and perform very poorly when normalized MCFOs are lager than 0.5. In [7] and [8], iteration algorithms are combined with MLEs to eliminate the MRI iteratively under flat-fading channels, however, these algorithms have relatively high complexity, and cannot be used in multipath channel since the complexity will be intolerable.

Notice that all of the aforementioned methods are based on the assumption of flat-fading channels or small CFO values ($\leq$ 0.5). However, it has been pointed out in [7] that the assumption of small CFO values might hold for point-to-point MIMO systems, but it is not reasonable for cooperative systems since the relays are spatial distributed and have independent oscillators. To the authors' knowledge, few synchronization method can be used in the multi-relay networks which in the presence of both large MCFOs and frequency selective channels.

To solve this problem, an efficient scheme for time and frequency synchronization over multipath channels is proposed without the assumption of small MCFOs. First a novel preamble utilizing CAZAC sequence is proposed. Taking advantage of the preamble structure, a path timing searching period is involved to reduce the complexity of the second stage. Then joint timing and integral frequency estimation based on the results of the first stage will be carried out to combat the influence of MRI. Finally, fractional frequency and fine timing synchronization will be carried out.

II. System Description

In this section, a model of cooperative relay system is described and then the joint timing and frequency synchronization method is introduced into cooperative relay networks.

A. System Model

A half-duplex multi-relay cooperative network adopting decode-and-forward (DF) protocol with one source node $\mathbb{S}$, M relay nodes $\mathbb{R}_k$ ($k = 1, 2, \cdots, M$), and a single destination node $\mathbb{D}$ is considered in Fig. 1. Synchronization for cooperative networks can be divided into two phases. In phase one, the transmitter broadcasts symbols to the relay nodes. In the second phase, each relay node transfer its distinct preamble to $\mathbb{D}$. Notice that synchronization in the first phase is similar to single input single output (SISO) systems. Thus we assume the offsets at each relay have been estimated and compensated perfectly, so only the synchronization problem in the second phase is considered here.

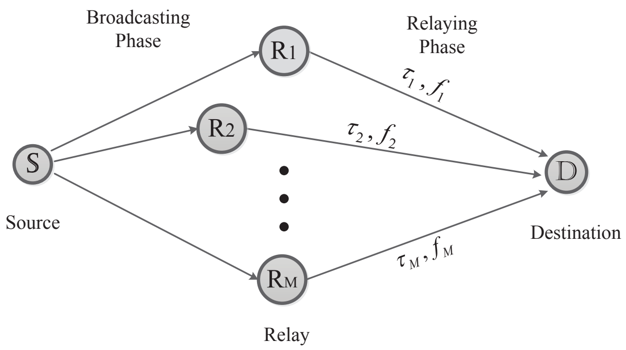

Fig. 1. The system model for the cooperative network.

Training Signal Model at the Destination: The baseband received training signal at the destination for a cooperative network consisting of M relay nodes is given by:

$$r(n) = \sum_{k=1}^{M} r_k(n) = \sum_{k=1}^{M}\sum_{l=0}^{L-1} h_k(l) t_k(n-\tau_k-l) e^{\frac{-j2\pi f_k n}{N}} + w(n)$$
$$n = 0, \cdots, N-1 \qquad (1)$$

where:

- N denotes the length of the peamble;
- τ_k is the unknown timing offset of the kth relay, normalized by the sampling time period;
- f_k is the CFO between the kth relay and $\mathbb{D}$, normalized by the subcarriers spacing;
- $w(n)$ is the AWGN at the destination with $\mathcal{CN}\left(0, \sigma_w^2\right)$.

B. Joint Timing and Frequency Synchronization in Cooperative Networks

In [9], the authors proposed a FFT-based joint timing and frequency synchronization method for OFDM systems. The basic idea of this method can be summarized as following: The received signal is multiplied by the known preamble at the destination. If it is a correct timing position, the output of the multiplier will be a constant amplitude sequence with linear shifting phase, which means a impulse will emerge at the position of frequency offset in frequency domain; otherwise, no impulse can be observed. Thus the joint estimation problem is equivalent to the detection of impulses in frequency domain. Using the same idea, we can derive the joint timing and frequency synchronization method for cooperative networks.

To estimate the offsets of the kth relay, the received signal is multiplied by the preamble $t_k(n)$, and the result will be

$$\begin{aligned}Q_k(d, f_k) &= \sum_{n=0}^{N-1} r(d+n, f_k) t_k^*(n)\\ &= \sum_{j=1}^{M}\sum_{l=0}^{L-1}\sum_{n=0}^{N-1} h_j(l) t_j(d+n-\tau_j-l) e^{\frac{-j2\pi f_j n}{N}} t_k^*(n) + w(n) t_k^*(n)\\ &= \sum_{l=0}^{L-1}\sum_{n=0}^{N-1} h_k(l) t_k(d+n-\tau_k-l) t_k^*(n) e^{\frac{-j2\pi f_k n}{N}}\\ &\quad + MRI + w(n) t_k^*(n),\end{aligned} \qquad (2)$$

where $r(d+n, f_k)$ denotes the nth sample of the received signal vector at time d which is affected by the normalized CFO of the kth relay f_k. The second term in (2) is the MRI and it is decided by the cross-correlation property between different preambles. When $d \in [\tau_k, \tau_k - L + 1]$, one channel path from the kth relay will arrive at the destination at time d, thus the first term in (2) can be divided into a coherent part and a random part, i.e.

$$Q_k(d, f_k) = C_k(l = d - \tau_k, f_k) + \Gamma_k(l \neq d - \tau_k, f_k), \qquad (3)$$

where:

$$C_k(l = d - \tau_k, f_k) = \sum_{n=0}^{N-1} h_k(d-\tau_k) |t_k(n)|^2 e^{-j\frac{2\pi n}{N} f_k} \qquad (4)$$

$$\begin{aligned}\Gamma_k = \sum_{n=0}^{N-1} (\sum_{l \neq d-\tau_k} & h_k(l) t_k(d+n-l-\tau_k) t_k^*(n) e^{-j\frac{2\pi n}{N} f_k}\\ & + MRI + w(n) t_k^*(n)).\end{aligned} \qquad (5)$$

The coherent part can only occur when an channel path is arrived, and an impulse can be observed in frequency domain. Therefore, joint timing and frequency synchronization is achieved when the coherent part is present, and a metric $I_k(\hat{d}_{ch}, f)$ is defined as following to find the coherent part

$$I_k(\hat{d}_{ch}, f) = \left| \sum_{i=0}^{N-1} r(\hat{d}_{ch} + i, f) t_k^*(i) e^{-j2\pi i f/N} \right|,$$
$$f = -N/2, -N/2+1, \cdots, 0, 1, \cdots, N/2, \qquad (6)$$

which can be determined by FFT. Time point $\hat{d}_{ch}$ is chosen from the timing checkpoints obtained in the first stage to reduce the number of times of FFT which will be specified later. If the maximum point of $I_k(\hat{d}_{ch}, f)$ exceeds the threshold δ_{Fk}, the f at the maximum point gives the coarse estimation of CFO, and $\hat{d}_{ch}$ corresponds to a strong channel path of the kth relay ($\hat{d}_{ch}$ is fixed when calculating $I_k(\hat{d}_{ch}, f)$ with FFT). The threshold δ_{Fk} is derived as:

$$\delta_{Fk} = \sqrt{-\ln(\mathrm{P_{FD}}/\lambda_F) 2\hat{\sigma}_{Fk}^2} \qquad (7)$$

where

$$\hat{\sigma}_{Fk} = \sqrt{2/\pi}(mean_f \left\{ I_k(\hat{d}_{ch}, f) \right\}), f \neq f_k, \qquad (8)$$

λ_F is the search window used for coarse CFO estimation, $\mathrm{P_{FD}}$ is the false detection probability. By using the threshold criterion, the proposed method is able to exclude timing instants which do not correspond to a strong arriving channel path and estimate the frequency offset of the kth relay.

III. Proposed Method

In this section, a multistage scheme illustrated in Fig. 2 is proposed. The checkpoints are obtained by utilizing auto-correlation in the first stage. Then these points will be used as the initialization of joint coarse timing and integer frequency estimation. After that, fractional frequency estimation and fine timing estimation will be carried out.

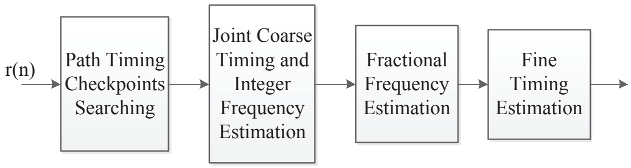

Fig. 2. Block diagram of the proposed synchronization method.

A. Preamble Design and Path Timing Checkpoints Searching

Path timing checkpoints searching plays an important role in the overall synchronization scheme over multipath fading channels. With this period, the number of the times of FFT in the next stage can be reduced significantly, since only the checkpoints will be involved. The estimator must be immune to large frequency offsets and produce only impulses that correspond to the arrival of the preambles from the channel paths. In [9] and [10], cross-correlation based methods are utilized to obtain the path timing checkpoints. However, they can not be directly used in cooperative relay systems, due to the presence of MTOs and MCFOs, and M correlators will be required at the destination.

In this subsection, we proposed a auto-correlation based method to attain a coarse estimator that is immune to MCFOs. An output of this estimator only indicates the arrival of a channel path, without the consideration of which relay it belongs to.

1) Preamble Structure: The preamble structure are re-designed to resist large MCFOs, as shown in Fig. 3.

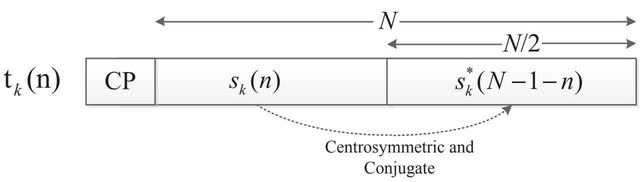

Fig. 3. The proposed preamble structure.

Each preamble of length N consists of two parts with equal length, and the second part is centrosymmetric and conjugate with the first part. The preamble assigned to the kth relay is $t_k(n)$, which satisfies $t_k(n) = t_k^*(N-1-n), \mathrm{n} = 0, \cdots, N-1$. The last G samples of $t_k(n)$ are used as cyclic prefix (CP) with length G. The preamble for each relay has the same structure, however with different $s_k(n)$ to distinguish from other relays.

2) Design of $s_k(n)$: To reduce the MRI in the second stage, we employ the CAZAC sequence to design $s_k(n)$, which have good auto-correlation property and constant magnitude in both the time domain and the frequency domain. A CAZAC sequence with length N_0 is given as:

$$c(n) = \begin{cases} e^{j\pi q n^2/N_0}, & \text{for even } N_0, \\ e^{j\pi q n(n+1)/N_0}, & \text{for odd } N_0, \end{cases} \tag{9}$$

where $n \in (0, \cdots, N_0 - 1)$ and q are relatively prime to N_0. If $c(n)$ is assigned to the 1th relay as $s_1(n)$, a cyclic shift version of $c(n)$ will be assigned to the next relay, where the cyclic shift length is K_0. Thus the $s_k(n)$ for the kth relay can be obtained by $c(\lfloor n + (k-1) \times K_0 \rfloor_{N_0})$. Notice that K_0 must be larger than $\max\{\tau_1, \cdots, \tau_M\}$, in order to maintain the orthogonality between preambles. Furthermore, the maximum number of active relays in the network is $\lfloor N_0/K_0 \rfloor$.

3) Path Timing Checkpoints Searching: Taking advantage of the preamble structure, an auto-correlation based metric conducted at destination will produce impulses that correspond to the arrival of the preambles from the channel paths of all relays. The checkpoints searching are derived as follows:

$$P(d) = \sum_{n=0}^{N/2-1} r(d+n) \cdot r(d+N-1-n). \tag{10}$$

Assuming the lth path of kth relay arrives at destination at time μ_k, the dominant term of the metric can be expressed as

$$\begin{aligned} P(\mu_k) &= h_k(l)^2 \sum_{n=0}^{N/2-1} t_k(n) t_k(N-1-n) \cdot e^{j\frac{2\pi(2\mu_k+N-1)}{N} f_k} \\ &= h_k(l)^2 \sum_{n=0}^{N/2-1} |s_k(n)|^2 \cdot e^{j\frac{2\pi(2\mu_k+N-1)}{N} f_k} \qquad (11) \\ &= \frac{N}{2} \cdot h_k(l)^2 \cdot e^{j\frac{2\pi(2\mu_k+N-1)}{N} f_k} \quad , \qquad (12) \end{aligned}$$

where we assume $s_k(n)$ is a constant amplitude sequence. It is obvious that CFO and channel gain only impact the phase of $P(\mu_k)$, while the amplitude is independent of CFO. Thus, the checkpoints $\hat{d}_{ch}$ are obtained by finding the γ number of largest value of $|P(d)|$ (γ is a parameter set beforehand.). Note

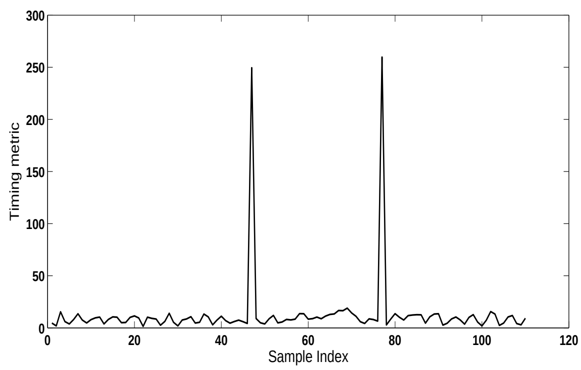

Fig. 4. Timing metric under no noise and channel distortion conditions (The number of relays is 2 and N=512, G=36, $\tau_1 = 47, \tau_2 = 77$)

that this metric may produce one or two pseudo peaks, so γ must be a litter larger than $M \times L$ to make sure every channel path has been included, where M is the number of relays and L is the order of multipath channels. Fig. 4 shows the proposed metric under no noise and channel distortion conditions, and it can be seen that each relay only correspond to one sharp impulse.

B. Joint Coarse Timing and Integer Frequency Estimation

This stage operates in the two dimensions of time and frequency to jointly determine a strong channel path timing and the integer frequency estimation of each relay. This estimator based on coherent cross-correlation has been introduced earlier in section II-B. To improve the performance of the estimator, consider a metric similar with [10], and following equations are calculated for the kth relay

$$\Psi_k(\hat{d}_{ch}, f) = I_k(\hat{d}_{ch}, f) + I_k(\hat{d}_{ch}, f+1)$$

$$f = -N/2, \cdots, 0, 1, \cdots, N/2 \ , \qquad (13)$$

where $I_k(\hat{d}_{ch}, f)$ is defined in (6). The timing checkpoints achieved in first stage are used as the initialization to reduce the computational complexity, and they are sorted in descending order of strength. For each timing checkpoint starting from the strongest, we compute the 1-D frequency offset metric $\Psi(\hat{d}_{ch}, f)$ using FFT, and if the peak of the metric exceeds the threshold η_F (which only happens when this timing checkpoint belongs to the kth relay), a successful estimation is obtained. The corresponding peak instant determines both the value of channel path timing and integer frequency estimation. Otherwise the next timing checkpoint is considered.

The process continues until the whole timing checkpoints are used and no successful estimation is obtained. In this situation, the maximum value determined the estimate results

$$\hat{f}_{k,I} = \arg\max_{f} \{\Psi_k(d_{ch}, f)\} \qquad (14)$$

$$\hat{d}_{k,path} = \arg\max_{d_{ch}} \{\Psi_k(d_{ch}, f)\} \ . \qquad (15)$$

To ensure reliable estimation, we set $\eta_F = 2\delta_F$, and δ_F is the threshold of $I_k(\hat{d}_{ch}, f)$ defined in (7). It is obvious that the offset between integer frequency estimation result and the true value will be less than one subcarriers spacing.

C. Fractional Frequency Offset Synchronization

If the frequency offset is integer, the adjacent values around the peak in frequency domain are very small when the timing position is correct. Otherwise the adjacent values may rise, so the algorithm in [11] is utilized to achieve an accurate result. Using the peak value $I_k(\hat{d}_{k,path}, \hat{f}_{k,I})$ and its adjacent points to estimate the fractional CFO

$$\hat{f}_{k,f} = \frac{I_k(\hat{d}_{k,path}, \hat{f}_{k,I}+1)}{I_k(\hat{d}_{k,path}, \hat{f}_{k,I}) + I_k(\hat{d}_{k,path}, \hat{f}_{k,I}+1)} \qquad (16)$$

As in [11], the estimation accuracy can be further improved as follows:

$$\hat{f}_{k,res} = \frac{I_k(\hat{d}_{k,path}, \hat{f}_{k,I} + \hat{f}_{k,f} + 0.5) - I_k(\hat{d}_{k,path}, \hat{f}_{k,I} + \hat{f}_{k,f} - 0.5)}{2(I_k(\hat{d}_{k,path}, \hat{f}_{k,I} + \hat{f}_{k,f} + 0.5) + I_k(\hat{d}_{k,path}, \hat{f}_{k,I} + \hat{f}_{k,f} - 0.5))} \qquad (17)$$

Finally, the CFO estimation is expressed as:

$$\hat{f}_k = \hat{f}_{k,I} + \hat{f}_{k,f} + \hat{f}_{k,res} \ . \qquad (18)$$

D. Fine Timing Synchronization

This stage is aim to find the first arriving channel path of the kth relay, because the strongest path may not be the first path in multipath fading channels. To estimate the first arriving path, the cross-correlation method used in [9], [10] as follows:

$$P_k(d) = \sum_{n=0}^{N-1} r(d+n) \cdot e^{-j\frac{2\pi(d+n)}{N}\hat{f}_k} t_k(n) \ . \qquad (19)$$

The time of the arrival of the first channel path is estimated as:

$$\tilde{\theta}_k = \arg\, \underset{d}{first} \{|P_k(d)| > \delta_T\}, d \in \left\{\hat{d}_{k,path} - \lambda_T, \hat{d}_{k,path}\right\} \qquad (20)$$

where $\delta_T = \sqrt{-\ln(\mathrm{P_{FD_T}}/\lambda_T) 2\hat{\sigma}_T^2}$

$$\hat{\sigma}_T = \sqrt{2/\pi}\left(\underset{d}{mean}\{|P_k(d)|\}\right), d < \hat{d}_{k,path} - \lambda_T - 1 \ .$$

$\mathrm{P_{FD_T}}$ is the probability of false detection in the timing axis, and all channel paths for one relay are expected to be received within $\lambda_T + 1$ samples ($\lambda_T \geq L - 1$).

IV. Simulation Results

A cooperative network consisting of 2 relays is considered. Without loss of generality only the performance for the first relay is presented. In each simulation, the transmitter is simulated according to the 3GPP LTE specifications. The entire bandwidth is 5 MHz, and the preamble defined in section III-A contains 512 samples with length 36 cyclic prefix. The cyclic shifting length K_0 is 64, and we also have $\mathrm{P_{FD_F}}$=$\mathrm{P_{FD_T}} = 10^{-6}$, λ_T= 36, γ = 12. Simulation channel models include flat-fading and an independent L = 5 paths Rayleigh fading channel with exponential power delay profile with the average power of $e^{(-\tau/L)}$. The timing delay is assumed of the uniform distribution over -40 to 40 and the normalized CFOs of two relays are $\{2.5, 1.4\}$ to prove the effectiveness when the CFOs are large.

Fig. 5 compares the MSE performance of the proposed timing scheme with conventional cross-correlation based synchronization method utilizing CAZAC sequence in [6] over multipath fading channels. It is obvious that the conventional method suffers a severe error floor due to the large CFOs. While, the new scheme reduces the effect of CFOs and outperforms the conventional method.

Fig. 6 presents the performance of the proposed timing synchronization method utilizing different preambles, including CAZAC, Walsh and m sequence. Apparently, CAZAC sequence has the best MSE performance, due to its perfect auto-correlation property. While Walsh sequence can hardly synchronize to the correct timing position, since it has poor

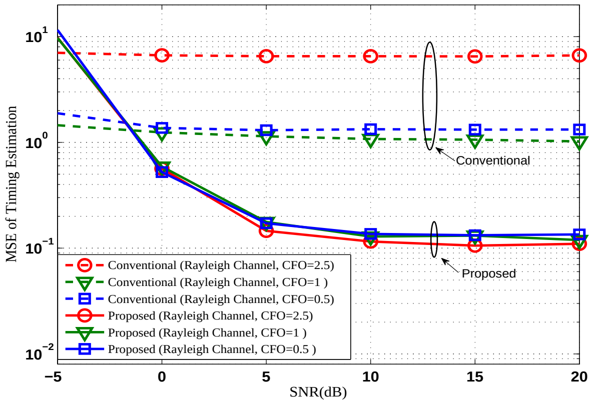

Fig. 5. Timing MSE of different estimators in multipath fading channel. (N=512, G=36, K_0=64).

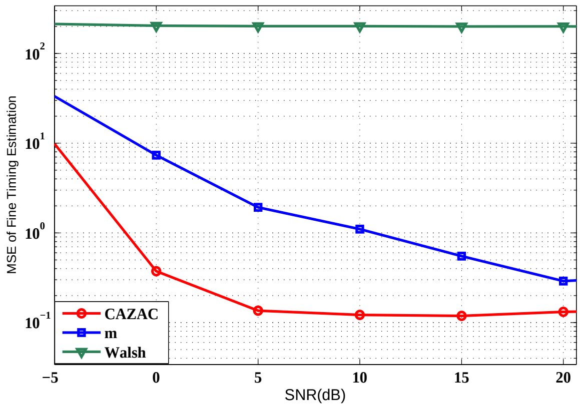

Fig. 6. Timing MSE of different preambles in multipath fading channels. (N=512 and G=36.)

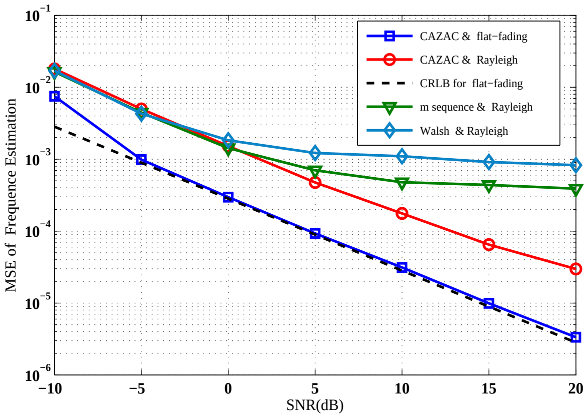

Fig. 7. Frequency MSE in different channels. (N=512 and G=36.)

auto-correlation property and performs very poorly in the fine timing stage.

Fig. 7 compares the MSE performance of the proposed frequency synchronization method under both flat-fading and multipath fading channels. The Cramer-Rao lower bound (CRLB) over flat-fading channel is also shown for comparison. Simulation results indicate that the estimator has good performance in both flat-fading and multipath fading channels. The performance of the proposed method using different preambles is also provided. As expected, CAZAC has the better performance than the other sequences.

V. Conclusions

In this paper, we presented a complete and practical time and frequency synchronization scheme for cooperative relay networks over multipath channels and it is robust in the presence of either small or large MCFOs. A novel preamble was designed to introduce the joint timing and frequency synchronization method into cooperative networks. Our simulation results demonstrate that the proposed method enhance the estimation performance remarkably.

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References

[1] J. Laneman, D. Tse, and G. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Trans. Inform. Theory*, vol. 50, no. 8, pp. 3062 – 3080, Dec 2004.

[2] M. Morelli, “Timing and frequency synchronization for the uplink of an OFDMA system,” *IEEE Trans. Commun.*, vol. 52, no. 2, pp. 296 – 306, Feb 2004.

[3] M.-O. Pun, M. Morelli, and C.-C. J. Kuo, “Maximum-likelihood synchronization and channel estimation for OFDMA uplink transmissions,” *IEEE Trans. Commun.*, vol. 54, no. 4, pp. 726 – 736, Apr 2006.

[4] Y. Tian, X. Lei, Y. Xiao, and S. Li, “ML synchronization algorithm and estimation bounds for cooperative systems,” in *Proc IEEE Pacific Asia Conf. on Circuits, Commun. and Systems (PACCS), China*, Aug 2010.

[5] Q. Huang, M. Ghogho, J. Wei, and P. Ciblat, “Practical timing and frequency synchronization for OFDM based cooperative systems,” *IEEE Trans. Signal Process.*, vol. 58, no. 7, pp. 3706 – 3716, Jul 2010.

[6] Y. Y. Zhang, J. H. Zhang, F. Sun, C. Feng, and P. Zhang, “A novel timing synchronization method for distributed MIMO-OFDM systems in multipath rayleigh fading channels,” in *Proc IEEE VTC Spring 2008*, May 2008.

[7] H. Mehrpouyan and S. Blostein, “Synchronization in cooperative networks: Estimation of multiple carrier frequency offsets,” in *Proc. IEEE ICC*, 2010.

[8] A. Nasir, H. Mehrpouyan, D. Blostein, and S. Durrani, “Timing and carrier synchronization with channel estimation in multi-relay cooperative networks,” *IEEE Trans. Signal Process*, vol. 60, no. 2, pp. 793 – 811, Feb 2012.

[9] A. B. Awoseyila, C. Kasparis, and B. G. Evans, “Robust time-domain timing and frequency synchronization for OFDM systems,” *IEEE Trans. Consum. Electron.*, vol. 55, no. 2, pp. 391 – 399, May 2009.

[10] H. Abdzadeh-Ziabari, “Robust timing and frequency synchronization for OFDM systems,” *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 3646 – 3656, Oct 2011.

[11] G. Ren, Y. Chang, H. Zhang, and H. Zhang, “An efficient frequency offset estimation method with a large range for wireless ofdm systems,” *IEEE Trans. Veh. Technol.*, vol. 54, no. 4, pp. 1892 – 1895, Jul 2007.