A Robust Coarse Timing Synchronizer Design for Cooperative Diversity OFDM System

Mudassar I. Cheema and Shoab A. Khan

***Abstract*—In this paper, a robust coarse symbol timing offset synchronizer design for cooperative diversity OFDM system is proposed. Further, a preamble format suitable for cooperative diversity scenario is presented. Then frame structure, preamble and cooperative protocol for transmitter and relay is elaborated in context of deployment of proposed algorithm. The proposed algorithm shows good probability of synch detection even in a Rayleigh fading channel. Furthermore, two low complexity versions for coarse timing metric estimation are also described. The performance of these algorithms is evaluated for orthogonal, independent and proposed preamble using Monte Carlo simulations.**

***Index Terms*—Synchronization, cooperative diversity, OFDM, preamble.**

I. INTRODUCTION

OFDM and MIMO are the technologies of choice to enable high data rate wireless communications. OFDM is capable of converting a single frequency selective channel into a frequency flat channel by dividing the available spectrum into a number of overlapping but orthogonal narrowband subchannels. Moreover, intersymbol interference (ISI) is avoided by adding cyclic prefix (CP) to each OFDM symbol. On the other hand, MIMO employs multiple antennas at the transmitter and receiver sides to open up additional parallel subchannels in spatial domain over the same frequency and time thus providing high data rates for a fixed bandwidth. The combination of MIMO-OFDM is technically very promising for high data rate wireless communication systems but the requirement of more than one transmitter antenna is not feasible for portable terminal devices due to cost , size and power constraints.

Cooperative Diversity techniques [1] can be used to relieve the Source and Destination side from multiple antennas that are otherwise required to harness spatial diversity benefits to mitigate signal fading [2]. An OFDM system based on this idea may be described as Cooperative Diversity OFDM system (CD-OFDM). In CD-OFDM, distributed multiple nodes (relays) form a virtual multiple antenna array thus replacing the multiple physical antennas. Fig.1 shows a CD-OFDM system comprising of a Source and a Relay that provide transmit diversity similar to an open loop MIMO system (2×1). It is assumed that only one relay participates but it can be extended to any number of relays by incorporation necessary modifications.

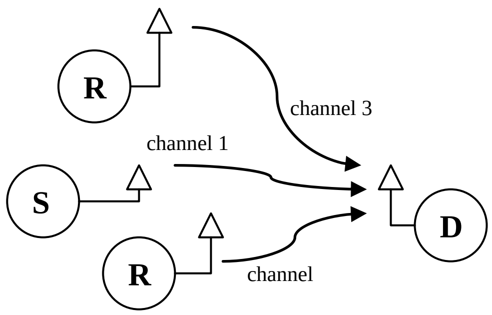

Fig. 1. Cooperative diversity system comprising of a source(S) and multiple relays(R).

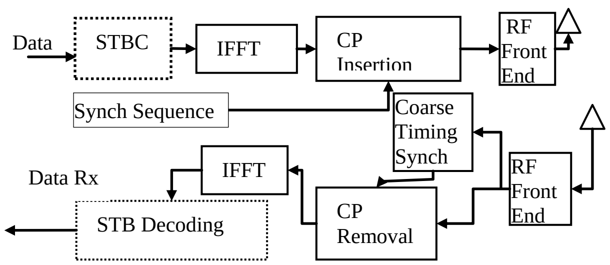

Fig. 2. Block diagram of transmitter and receiver used in a CD-OFDM system. Dotted blocks used only during cooperative phase.

In this paper, a new preamble and coarse timing synchronization method is proposed for CD-OFDM system. For any OFDM based system, coarse timing estimation is required to determine the start of frame and Fast Fourier Transform (FFT) window for each OFDM symbol. A number of methods have been published in literature for timing synchronization in OFDM systems [3]-[6]. The CD-OFDM systems are much more sensitive to synchronization errors as compared to simple OFDM system due to multi-user environment [7], [8]. Only few papers explored synchronization of Cooperative diversity systems [9].

This paper is organized as follows. Section II introduces the CD-OFDM system and proposed preamble structure for DF mode. Synchronization (coarse timing) algorithms are developed in Section III. Section IV presents the simulation results to validate the proposed algorithms. Finally, paper is concluded in Section V.

Notations: Small letters are used for time domain signals and capital letters are used for frequency domain signals. The node (x) represents Source (S) , Relay (R) and Destination(D). The transmission phase (y) represents the Listening phase(L) and Cooperation phase(C) .The link (l) from Source to Relay, Source to Destination and Relay to Destination are denoted by SR, SD and RD respectively. *, FFT and ε denotes convolution, Fast Fourier Transform

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and Expectation operations respectively.

II. System Description

A. CD-OFDM Signal and Channel Model

A simplified block diagram for Transmitter and Receiver is shown in Fig. 2 that only shows system components necessary for explaining the proposed algorithms. Source and Relay are OFDM based systems. An OFDM system using N point Inverse Fast Fourier Transform (IFFT) is considered where each OFDM symbol is composed of N_u $(N_u \leq N)$ modulated subcarrier symbols $a_{n,k}$ where n denotes OFDM symbol time index and k denotes subcarrier frequency index.

OFDM symbol length in a sample spaced system is $N_c = N_u + N_g$ where the guard interval length in samples is N_g . The equivalent representation for the k samples of transmitted baseband n_{th} OFDM symbol is as below [3].

$$s_x(k) = \frac{1}{\sqrt{N}} \sum_{m=-\frac{N_u}{2}}^{\frac{N_u}{2}-1} a_{n,k}\, e^{j2\pi\left(\frac{k.m}{N}\right)} \qquad -N_g \leq k \leq N-1 \tag{1}$$

Consider a frequency selective multipath fading channel $h_l(\tau, t)$ that combines the effect of actual channel impulse response (CIR) and transmit filter $g_T(\tau)$

$$h_l(\tau, t) = \sum_i h_{l,i}(t)\delta(\tau - \tau_i) \qquad i = 0,1, \dots \dots \dots . K_l - 1 \tag{2}$$

Note that $h_{l,i}(t)$ and τ_i are the complex path gain and delay at time t for link. τ_{max} is the maximum channel delay spread where $\tau_{max} = \tau_{i=K_l-1}$ and K_l is the length of channel impulse response for link l. For sample spaced path delays $(\tau_i = i)$ and h_i represents discrete-time channel impulse response. Assuming a flat receive filter, the receiver input signal at node(x) during phase(y) is:

$$r_{x,y}(t) = \sum_i h_{l,i}(t) s_x(t - \tau_i) + w(t) \tag{3}$$

The equivalent representation for the k samples of received baseband n_{th} OFDM symbol is

$$r_{x,y}(k) = \sum_{i=0}^{K-1} h_{l,i} s_x(k - \tau_i) + w(k) \tag{4}$$

where $w(k)$ is the sample of zero mean complex Gaussian noise process with variance σ_w^2 .

B. Frame Structure and Proposed Preamble

CD-OFDM frame comprises of two subframes: Listening subframe and Cooperation subframe [10]. Each subframe comprises of data and a time domain preamble.

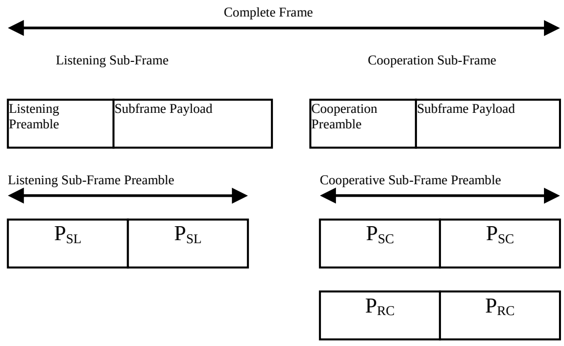

Fig. 3. Frame structure of CD-OFDM comprising listening and cooperative subframe.

Frame structure and preamble are shown in Fig. 3. The preamble sequence $\{p_S[n]: 0 \leq n \leq N_{pre}\}, \{p_R[n]: 0 \leq n \leq N_{pre}\}$ defines a N_{pre} samples Source and Relay preamble respectively with $L_{pre} \geq 1$ periods. In Cooperative Phase of CD-OFDM, the received signal is a superposition of transmitted signals from Source and Relay. P_{xy} represents the preamble transmitted by $x = S \ or \ R$ during $y = C \ or \ L$ phase.Thus, the preamble of Source and Relay need to be constituted and transmitted in such a way that mutual interference is least and accurate synchronization is possible. Orthogonal and Independent preamble formats are mostly used for multi-user systems. These patterns alongwith their half length counterparts are shown in Fig.4. Orthogonal Preamble transmits (nearly) orthogonal patterns simultaneously from Source and Relay. Independent Preamble transmits from either Source or Relay at one time thus ensuring orthogonality in time domain.

A novel preamble format is proposed that combines the best properties of both. It is named CD-Hybrid (Cooperative Diversity – Hybrid) preamble because it suites best to cooperative diversity scenario. It has a null in first half of Relay preamble that permits sufficient time for decoding at Relay (DF type) prior to retransmission. Preferred paired Golay sequences of OFDM symbol length and half OFDM symbol length are used in CD-Hybrid preamble. Preamble is designed in a way that same preamble could be used for synchronization and channel estimation. Two important features of preamble are:

First, time domain preamble is used because it simplifies the time synchronization and channel estimation algorithms.

Second, preferred pair gold sequence is used for Source(S) and Relay(R) due to its better peak-to-average-power-ratio (PAPR), autocorrelation and cross correlation properties in multiuser environment [11].

C. Space Time Cooperation Architecture

Transmission of a single frame is completed in two phases: the listening phase and cooperation phase as described in [9]. In the listening phase, only Source broadcasts to Relay and Destination without any space time coding. During the Cooperation phase, the behavior of Relay and Destination is dictated by successful decoding at respective nodes. If Destination successfully decodes during Listening phase then it ignores all transmissions in Cooperation phase. In case of decoding failure, Destination receives the space time coded transmission from Source and Relay for retrying decoding. Source always retransmits its space time coded frame during Cooperation phase. Relay transmits a space time coded frame during Cooperation phase if decoding is successful during Listening phase otherwise remains silent. The space time coded sub frames of Source and Relay are constituent half portions of the complete Listening phase space time coded frame. There could be different ways of capitalizing from this space time diversity setup but are out of scope of this paper as it focuses on synchronization and channel estimation only.

The geometric gain G_l for different links is as under [9].

$$G_l \stackrel{\text{def}}{=} \frac{\mathrm{E}\left[\sum_{i=0}^{K_l-1}|h_{l,i}|^2\right]}{\mathrm{E}\left[\sum_{i=0}^{K_{SD}-1}|h_{SD}[i]|^2\right]} \tag{5}$$

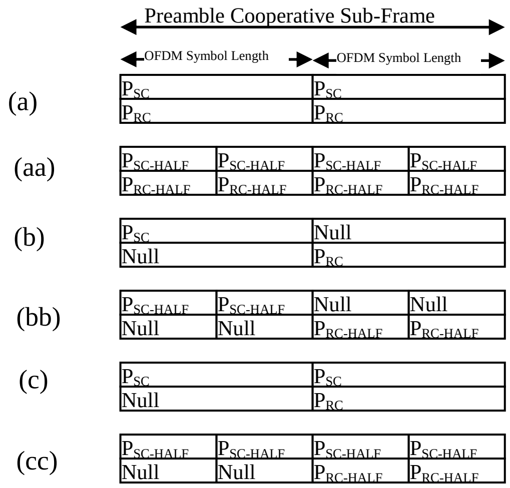

Fig. 4. (a) Orthogonal preamble pattern. (b) Independent preamble pattern. (c) CD-hybrid preamble pattern for cooperative phase.

III. Proposed Synchronization Method

The purpose of coarse Symbol timing Synchronization is to identify the start of frame so that cyclic prefix could be removed and set of samples for subsequent fft operation is flagged correctly. Timing synchronization during Listening phase is similar to any other OFDM system. But In Cooperation phase, synchronization becomes a bit different due to multi-user scenario. Taking symbol timing offset and carrier frequency offset into consideration, the received signal $r_{x,y}(k)$ at node $(x = R \text{ or } D)$ for Listening Phase$(y = L)$ becomes:

$$r_{x,L}(k) = \exp(j\varphi_l)\exp\left(j\frac{2\pi k \nu_l}{N}\right)\sum_{i=0}^{K-1} h_{l,i}s_l\left(k - \tau_{l,i}\right) + w(k) \tag{6}$$

and received signal for Cooperation phase at destination is:

$$\begin{aligned} r_{D,C}(k) &= exp(j\varphi_{SD})\, exp\left(j\frac{2\pi k \nu_{SD}}{N}\right)\sum_{i=0}^{K-1} h_{SD,i}s_{SD}\left(k - \tau_{SD,i}\right) \\ &+ exp(j\varphi_{RD})\, exp\left(j\frac{2\pi k \nu_{RD}}{N}\right)\sum_{i=0}^{K-1} h_{RD,i}s_{RD}\left(k - \tau_{RD,i} - \rho\right) + w(k) \end{aligned} \tag{7}$$

where ν_l is the carrier frequency normalized by the subcarrier spacing , φ_l is an arbitrary carrier phase factor , $h_{l,i}$ is a specific channel impulse response tap , $\tau_{l,i}$ is timing offset and ρ is timing offset between received signal from Source and Relay.

A. Coarse Timing Estimation

For derivation of timing algorithm, it is assumed that target signal is preceded by channel noise. This algorithm uses difference between squared distances of two parts of M samples each separated by Q samples for calculating timing metric. Three different versions are presented bellow with decreasing order of complexity. Type-3 algorithm is specially suited for burst transmission.

Type-1

$$\gamma_{coarse}(d) = \sum_{i=0}^{M-1}\frac{(|r(d+Q+i|^2 - |r(d+i|^2)}{(|r(d+Q+i|^2 + |r(d+i|^2)} \tag{8}$$

Type-2

$$\gamma_{coarse}(d) = \frac{1}{\alpha(d)}\sum_{i=0}^{M-1}(|r(d+Q+i|^2 - |r(d+i|^2) \tag{9}$$

where

$$\alpha(d) = \sum_{i=0}^{M-1}|r(d+Q+i|^2 + |r(d+i|^2$$

Type-3

$$\gamma_{coarse}(d) = \frac{1}{\beta}\sum_{i=0}^{M-1}(|r(d+Q+i|^2 - |r(d+i|^2) \tag{10}$$

where β is a scaling factor that is dependent on SNR but for sake of simplicity it may be fixed. This paper uses $M = \beta = Q = \frac{N}{2}$.

The coarse timing estimator flags the largest amplitude of the timing metric as start of frame (d_0) such that it is greater than coarse timing metric threshold γ_{th}.

$$\hat{d}_0 = arg_{d}^{max}\,\{\gamma_{coarse}(d)|\,\gamma_{coarse}(d) \geq \gamma_{th}\,\} \quad d = 0,1,\ldots\ldots,\frac{N}{2} \tag{11}$$

Estimated start of frame is pre-advanced by d_{adv} samples to make the estimator robust in case of multipath channel so that it remains in the ISI free region.

$$\hat{d}_{coarse} = \hat{d}_0 - d_{adv} \tag{12}$$

IV. Performance Evaluation, Simulation Results and Discussion

The performance of proposed algorithms is evaluated through computer simulations. The CD-Hybrid preamble of two OFDM symbol lengths is used. The proposed preamble exhibit good PAPR, autocorrelation and cross correlation properties that subsequently facilitate development of synchronization and channel estimation algorithm [11].

The Cooperative Diversity network comprises of one Source node, one Relay node and one Destination node. All nodes are OFDM based systems using QPSK modulation.

All simulations are run in baseband and no pulse shaping or frequency up-conversion is done. Rayleigh, Rician and static ISI channels have 16 taps with four taps spacing. Rayleigh fading channel has exponential power delay profile with first to last tap ratio of 20 dB. K-factor for Rician channel is four.

In Fig. 5, Coarse timing method (type-3) is used for different SNR scenario during Listening phase. This figure shows results for SD link using 1024 subcarrier OFDM system with 10% guard interval. Transmitted Frame includes "time domain preamble" and "information samples" of two OFDM symbol lengths each. Frame is prefixed and suffixed by "noise only samples". In order to evaluate the probability of missed detection(P_{missed}) and probability of false detection(P_{false}), 10^5 simulation runs are performed for a 16 tap Rayleigh channel. Simulation shows that P_{missed} curves are distinctively separated from P_{false} curves which results in good synch detection.

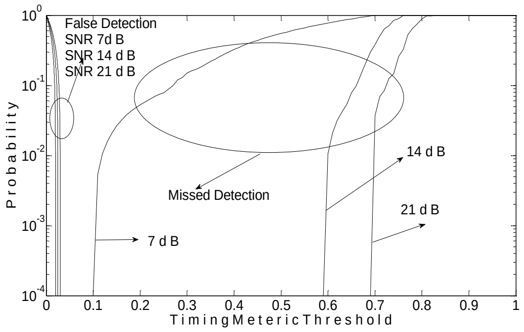

Fig. 5. Synchronization detection performance of coarse timing synchronizer (Type-3) during listening phase.

In Fig. 6, variance of timing metric for Type-1, Type-2 and Type-3 algorithm for cooperative phase in Rayleigh channel is compared for different preamble types. For Type-1 algorithm, CD-Hybrid preamble performs better for low SNR but Independent preamble leads marginally on high SNR. For Type-2 algorithm, all three preambles perform equally well on high SNR but overall worse than Type-1. For Type-3 algorithm, Independent preamble performs better than CD-hybrid.

In Fig. 7, a comparison of Type-1 algorithm using CD-Hybrid preamble is shown with other algorithms in literature like Cox [4] and Minn [12]. The AWGN, static ISI, Rician and Rayleigh channels are used for simulation.

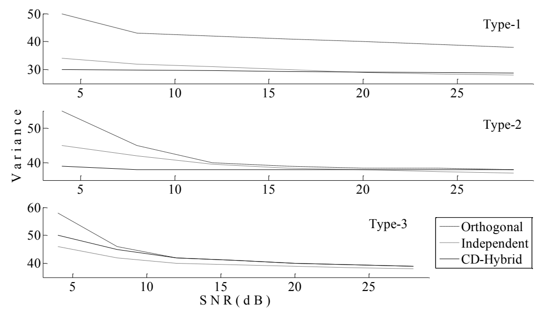

Fig. 6. Variance (sample) 2 of coarse timing metric (Type-1, Type-2, Type-3) for cooperation phase. Orthogonal, independent and CD-hybrid preamble patterns compared.

V. Conclusion

The OFDM and MIMO technologies have been successfully used in a number of standards to provide high data rates in a multipath fading environment. Commercial manifestations of these technologies include IEEE 802.11 a/n, 802.16e, 3GPP Long Term Evolution (LTE), Digital Video Broadcast for terrestrial and handheld (DVB-T/H) and DVB-T2. However, in mobile communications, it is not feasible to have multiple antennas at the user end. That is where cooperative diversity systems come in. CD-OFDM systems may be widely adopted in future mobile communication systems due to their favorable features. This paper has presented a preamble and coarse timing system for CD-OFDM system and performance of both algorithms is compared with already existing algorithms for OFDM systems. Simulation results in Fig. 7 show that performance of proposed algorithms in multi-user environment is better than reference algorithms.

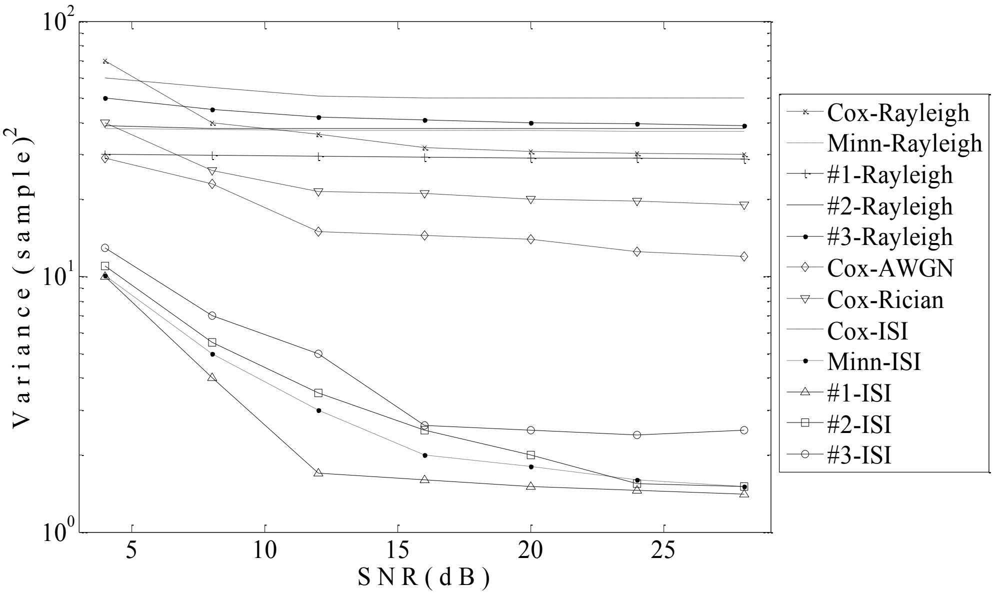

Fig. 7. Cooperative diversity system comprising of a Source(S) and multiple Relays(R) used for comparison with other well known algorithms.

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