A Method for Time and Frequency Synchronization in a Cooperative Communication System

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***Abstract*—In this paper, we present a method for time and frequency synchronization in relay based cooperative communication system. The system consists of Source, Destination and two Relay nodes. A generic frame structure is devised to meet the space-time relaying mechanism when a particular node receives plurality of signals from multiple transmitters via different wireless links. We proposed timing synchronization dealing with multiple timing offsets and frequency synchronization scheme that is unaffected by the CFO due to relays. We evaluated the probability of correct timing detection and mean of frequency error at different signal to noise ratios under ideal and realistic channel conditions.**

I. Introduction

Cooperative relaying stands to be an attractive solution to counteract the issue of devices with multiple antennas. The basic principle is to construct a virtual multiple-antenna system by allowing the neighboring nodes to share their radio resources.So with proper cooperation strategies the same benefits of multiple antenna systems can be achieved in a cooperative system.Compared to conventional relaying,it utilizes both the direct source-destination as well as the relay-destination link. In the present system, a well-designed space time diversity protocol [4] is implemented on top of a transmission technology such as OFDM (Orthogonal Frequency Division Multiplexing).

A wireless communication scenario where the source terminal S transmits information to the destination terminal D with the assistance of relay terminals R_m, $m = 1, 2, ...N - 1$ is considered. All the nodes are equipped with single transmit and receive antenna. Half duplex one-way relay network which operates on decode and forward cooperation scheme is considered. The relay employs a full physical layer transceiver and attempts to decode (with zero errors in the header) every transmission from the source. It initiates a transmission using the decoded bits as the input to its own OFDM transmitter after adding necessary training and header sections to the decoded data.

The transmitter structure mimics the IEEE 802.11a standard [2]. Pre-Cancellation of Carrier Frequency Offset (CFO) as shown in Fig.1 with dotted block, is only at the relay transmitters [5].The intended receiver i.e., Relay or destination first performs the energy detection, receive filtering, timing and frequency offset estimation to establish the synchronization and then performs channel estimation of the source to destination (SD), source to relay (SR) relay to destination(R_mD) and relay to relay (R_mR_m),$\{m$=$1, 2\}$ links using the received preamble signals.

Multiple nodes in these cooperative systems are equipped with their own oscillators which result in multiple frequency offsets. Multiple timing offsets arise due to the physical separation of the transmit nodes, which lead to different propagation delays for different links arriving at the destination. The synchronization algorithm in [1] is not directly applicable to cooperative systems.Method in [10] has a preamble design but doesn't handle multiple timing offsets and [9] performs multiple timing correlations over longer search periods. Also method in [8] involves sub-space decomposition algorithm with multi-dimensional search for correlation peak and dependent on tile length. So design of a simple approach to handle these timing and frequency offsets is one of the challenging issues in implementing a space-time cooperative system.

In this paper we address the timing and frequency synchronization problem in distributed space time cooperative system with two relays and can be extended for multiple relays. This paper is organized as follows. Section II outlines the details of the cooperative OFDM system. Section III builds the timing and frequency synchronization algorithms. Section IV provides the performance of the system and finally conclusions are presented in Section V.

II. Cooperative OFDM System

A. Proposed Frame Structure

Our physical layer operating in space-time cooperative scenario adopts the following frame structure partially inspired by the IEEE 802.11a standard [2]. The frame structure(Fig.3) is variable in each time slot and the number of components included in it change according to the operating time slot.In general, the frame is composed of three components: Preamble,Signal and Frame Payload. Preamble is split into Short training field and Long training field. The short training field is used for AGC, Signal Detection, Coarse timing and frequency synchronization. The long training field is used for Fine timing and Frequency synchronization, Channel Estimation.These short and long training sequences are desired to have good auto-correlation and cross correlation properties. Short training field $\{S_i[n]\}$ is a $\{+1, -1\}$ sequence where the subscript stands for the node i.e., $i = S$ and $i = R_m$where $m = 1, 2$. Long training field $L1_i[n], L2_i[n]$ and $L3_i[n]$ are Golay complementary sequences employed for their favorable peak

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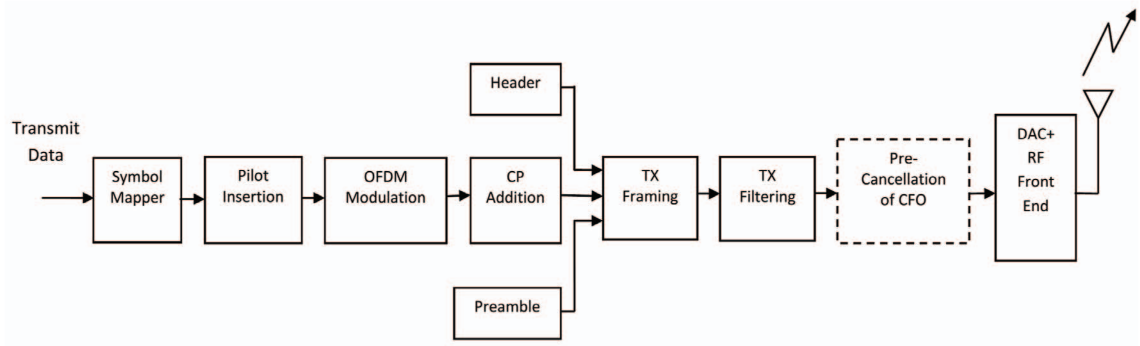

Fig. 1. Block Diagram of Transmitter

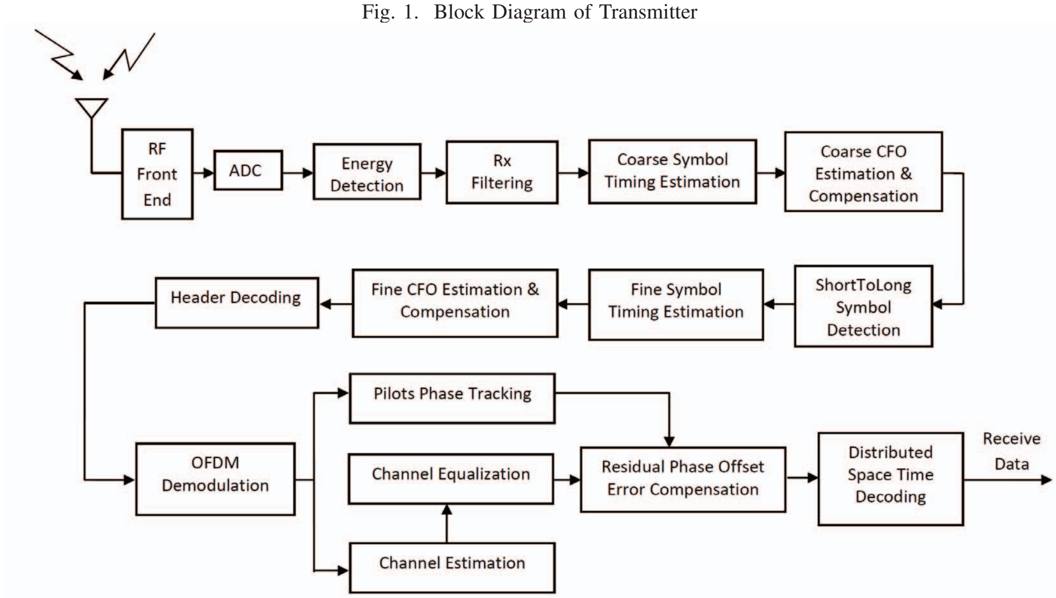

Fig. 2. Block Diagram of Receiver

to mean envelope power. To ease with the synchronization, we enforce that each of these sequences L1, L2 and L3 are complementary to each other and are obtained from Golay Complementary pair (GCP). The preamble is followed by a SIGNAL field $LSIG$ which represents the part of header field containing the information related to length of data, code rate, time slot information, modulation, coding scheme and other parameters.

This preamble structure is common to all the transmitters viz., Source, Relay1 and Relay2 in first time slot. However, the transmitters at Source, Relay1 and Relay2 may append additional long training fields to the existing preamble proportional to the time slot they are currently operating in. Cyclic shifts are also applied to prevent unintended beamforming when correlated signals are transmitted in multiple space-time streams (from Source, R1, and R2).

B. Signal and Channel Model

Let $i = S, R, D$ stand for the source,relay and destination nodes and let $l = SD, SR, RD, RR$ denote the SD link, SR link, RD link and RR link respectively. To make the signal descriptions simple, we ignore the transmit windowing under the assumption that the error performance is unaffected when the delay spread and timing errors are less than that of cyclic prefix. The lowpass equivalent of the training signal in time slot 3 is given as

$$\begin{aligned} s^i_{Training}(t) &= s^i_{STF}(t) + F(i, N_{CTS} - 2) * s_{LTF1}(t - t_{LTF1}) \\ &+ s^i_{SIGNAL}(t - t_{LSIG}) + F(i, N_{CTS} - 1) * s_{LTF2}(t - t_{LTF2}) \\ &+ F(i, N_{CTS}) * s_{LTF3}(t - t_{LTF3}) \end{aligned} \tag{1}$$

where a particular field description is given as

$$s^i_{Field}(t) = w_{Field}(t) * \frac{1}{\sqrt{N_{Field_{length}}}} * \sum_{k=-26}^{26} Field_k(t - T^i_{CS}) \exp(j2\pi k \Delta f(t - T^i_{CS}) \tag{2}$$

The field may correspond to Short, Long or Signal fields. According to the frame structure, the transmit frame is represented as

$$s^i_{PACKET}(t) = s^i_{Training}(t) + s^i_{DATA}(t - t_{DATA}) \tag{3}$$

$w_{Field}(t)$ are rectangular pulses of duration T_{Field}. $F(i, N_{CTS})$ denotes the orthogonal matrix whose rows are equal to i^{th} transmit chain and columns are equal to N_{CTS}:

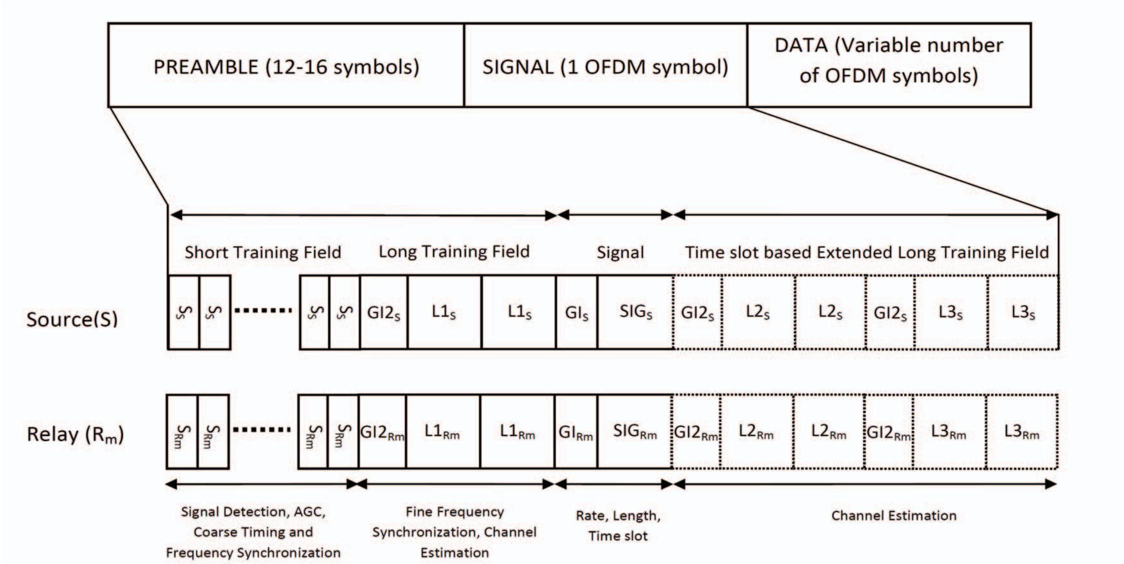

Fig. 3. Transmitter Frame Structure

Current time slot. We denote Source as 1st transmit chain. Relay1 as 2nd transmit chain. Relay2 as 3rd transmit chain. $t_{LTF1} = T_{SHORT}, t_{LSIG} = t_{LTF1} + T_{LONG}, t_{LTF2} = t_{LSIG} + T_{SIGNAL}, t_{LTF3} = t_{LTF2} + T_{LONG}$. $T_{CS}^{i_{Tx}}$ is the Cyclic Shift for the specific transmit chain i_{Tx}. All these timing constants are fixed based on the simulation parameters used to evaluate the performance of the system. Let us denote the signal $s^i_{PACKET}(t)$ as $s_i(t)$ for simplicity purpose. The channel of each wireless link is assumed to vary between time slot and is constant for a given time slot. The channel impulse response for each link is modeled as a frequency selective tapped delay line with exponential power delay profile :

$$h_l(n) = \sum_{p=0}^{N_l-1} h_{l,p}\delta(n-p) \tag{4}$$

where N_l denotes the number of multipaths for the link l, $\delta(.)$ denotes the Dirac delta function. The channel gain of each path follows an independent complex Gaussian distribution. The sampled baseband received signal from the node $i = S, R$ through the link l is given as

$$r_l^i[n] = \exp(\frac{j2\pi\epsilon_l n}{N}) \sum_{p=0}^{N_l-1} h_l[p]s_i[n-p-\tau_i] + w[n] \tag{5}$$

$w[n]$ denotes the additive white gaussian noise with zero mean and variance σ_w^2. ϵ_l and τ_i denote the carrier frequency offset for link l and timing offset at each node i.

C. Space Time Cooperation Protocol

Protocol B of [4] with an addition of a link between the relays (Fig. 4) is considered in our present system. Here the relay is active in all time slots. As soon as a particular relay receives its intended signal, it decodes and forwards the data to the destination terminal and repeats this for each time slot

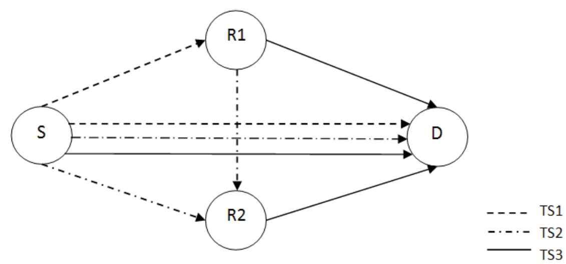

Fig. 4. Schematic representation of Relay assisted Cooperation in different time slots(TS)

TABLE I
COOPERATIVE TIME SHARING PROTOCOL SHOWING THE EXCHANGE OF INFORMATION AT DIFFERENT NODES

Time Slot 1	**Time Slot 2**	**Time Slot 3**
$S(x_1) \to D$	$S(x_2) \to D$	$S(x_3) \to D$
$S(x_1) \to R_1$	$S(x_2) \to R_2$	$R_1(x_1) \to D$
$S(x_1) \to R_2$	$R_1(x_1) \to D$	$R_2(x_2) \to D$
	$R_1(x_1) \to R_2$	

(see Table I). where $S(x_j) \to R_m$ indicates the transmission of modulated frame x_j from the source terminal to the m^{th} relay node.Similarly $S(x_j) \to D$ indicates the transmission of x_j from the source terminal to the destination.

III. PROPOSED TIMING AND FREQUENCY SYNCHRONIZATION METHOD

The receivers at the Relay and Destination establish timing and frequency in different time slots by making use of the repetitive structure of the preamble intended to ease the synchronization. Consider the received signals at the destination in third time slot($TS3$)

$$r[n] = \exp(\frac{j2\pi\epsilon_{SD}n}{N}) \sum_{p=0}^{N_{SD}-1} h_{SD}[p]s_S(n-p-\tau_S)$$
$$+\exp(\frac{j2\pi\epsilon_{R_1D}n}{N}) \sum_{p=0}^{N_{R_1D}-1} h_{R_1D}[p]s_{R1}[n-p-\tau_{R_1}]$$
$$+\exp(\frac{j2\pi\epsilon_{R_2D}n}{N}) \sum_{p=0}^{N_{R_2D}-1} h_{R_2D}[p]s_{R_2}[n-p-\tau_{R_2}]$$
$$+w[n] \quad (6)$$

Prior to timing synchronization, energy detection is performed to indicate the presence of significant incoming signals. For this, the energy of the received signal is computed and compared with a threshold γ which is set according to the constant-false-alarm-rate-criterion as in [1].This threshold is dependent on the noise power at the destination and the probability of false alarm P_{FA}.

A. Timing Synchronization

The timing synchronization is categorized into three sequential stages: coarse time synchronization, long training symbols detection and fine time synchronization. The coarse timing recovery relies on searching for a short training symbol with identical portions in time domain. This module is followed by frame synchronization which determines the frame boundary of long training symbols. Coarse timing estimate has a deviation of few samples from the actual time index which necessitates the use of fine timing synchronization. The third and final stage is fine timing synchronization which establishes the boundaries of long training sequence.

1) Coarse timing synchronization: The coarse timing recovery relies on searching for a short training symbol with identical portions in time domain. We use the local STF sequence s_S of the source to perform cross correlation with the received samples.

$$\Phi[\delta] = \sum_{n=0}^{N-1} r[n+\delta]s_S^*[n] \quad (7)$$

N_{cp} is the number of samples used for the correlation and is equal to length of cyclic prefix. The coarse timing estimate is then obtained as

$$\hat{\delta}_{ct} = \underset{\delta}{\text{argmax}}\{\Phi[\delta]\} \quad (8)$$

Under a multipath channel and when the timing offsets $\tau_S, \tau_{R_1}, \tau_{R_2}$ are non-zero, this correlation produces multiple peaks and may yield a timing that has a deviation from actual timing which can be resolved with fine timing estimation.

2) Long Symbol Detection: Long symbol detection module establishes the start of Long training field. For this, auto-correlation between the received short symbols is performed as given in eqn (9)

$$E_{corr}[\mu] = \sum_{n=0}^{N-1} r[n+\mu]r^*[n+\mu+N] \quad (9)$$

The energy of the received short symbol is computed as

$$E[\mu] = \sum_{n=0}^{N-1} |r[n+\mu+N]|^2 \quad (10)$$

A timing metric is defined as

$$\psi[\mu] = \frac{E_{corr}[\mu]}{E[\mu]} \quad (11)$$

The timing metric $\psi[\mu]$ is compared with a predefined or adaptive threshold Γ until $\psi[\mu] < \Gamma$ and at this point the timing boundary is detected as $\hat{\mu}_{SL} = \mu$.The threshold is set according to the probability of miss (P_{MD}) and correct detection (P_D).

3) Fine timing Synchronization: We extend the idea of method in [6] which includes determining a normalized correlation signal based on correlation between the received LTF symbol and a reference symbol for each of the receiver chains for different lags. Also, the method includes estimating an energy window length for the normalized correlation signal. The energy window length includes at least one of channel delay spread and a maximum cyclic shift applied to the signal. The method then includes estimating the symbol boundary associated with the received LTF symbol based on a position of peak energy of the normalized correlation signal using the estimated energy window length. The detailed steps are as follows: Compute the correlation between the received signal $r[n]$ and a reference signal $L1_S[n]$ during the long training field for different lags,

$$P[\delta] = \sum_{n=0}^{N-1} r^*[n+\delta]L1_S[n] \quad (12)$$

To estimate the width of the delay spread including cyclic shift if any, we perform the smoothing on using the window length W_s

$$Q[\delta] = \sum_{v=0}^{W_s} P[\delta+v] \quad (13)$$

The parameter W_s is tunable and initially we have taken its value as half the length of Cyclic prefix. Then, find the peak of $Q[\delta]$, a samples index d_l on left side to peak where $Q[\delta]$ crossing threshold T_l and its position d_r on the right side to peak where $Q[\delta]$ falling below threshold T_r . Using d_l and d_r, estimate the best window length for energy computation as

$$W_E = d_r - d_l + 1 \quad (14)$$

The window length W_E estimated is used to compute the energy of correlation as

$$E[\delta] = \sum_{v=0}^{W_E} P[\delta+v] \quad (15)$$

Then, the fine symbol boundary estimate is given by

$$\delta_{ft} = \max_{\delta}\{E[\delta]\} \quad (16)$$

Using the symbol boundary estimate we perform the rest of the operation to decode signal fields. If the parameter in the signal field, the number of space time streams is greater than one, the symbol boundary estimated is advanced by appropriate cyclic shift delay (CSD) value.

$$\delta_{ft} = \delta_{ft} + CS_{samples} \tag{17}$$

In scenarios where the channel in one of the links $l = SD, R_1D, R_2D$ is bad, we might get only a single correlation peak for a 3 transmit configuration. We do not know which stream contributes to that peak and hence, if we shift by CSD amount we might exceed the Cyclic Prefix boundary. To encounter such cases, we are not shifting the symbol boundary by CSD when we have a single peak. We detect the presence of a single peak when the length of smoothening filter W_s equals the energy window length W_E .

B. Frequency Offset Estimation and Compensation

In this section,the technique to synchronize the carrier frequencies of the relays to that of the source followed by the method for estimating the carrier frequency is discussed.

The carrier frequency offset estimate is obtained in two stages, the coarse and the fine estimate. The received symbols corresponding to the short training fields, after coarse symbol timing synchronization are used to obtain the coarse frequency estimate and the received symbols corresponding to the long training fields, after fine symbol timing synchronization are used to obtain the fine frequency estimate.

Consider time slot 1, where only the source transmits the data, the destination and relays estimate the carrier frequency relative to source.The estimates of carrier frequency at Relay1, Relay2 and Destination are given as in [3]

$$\Delta f_{SR1} = f_S - f_{R1}, \tag{18}$$

$$\Delta f_{SR2} = f_S - f_{R2} \tag{19}$$

$$\Delta f_{SD} = f_S - f_D \tag{20}$$

However in time slot 2 and 3, the receiver observes multiple frequency offsets corresponding to the transmissions of the source and relays, which cannot be directly estimated using the conventional algorithms provided in literature. Here we describe a technique where in the carrier frequency of the relays is matched to that of the source, thereby matching the carrier frequency of the composite signal to that of the source carrier frequency.The basic process for pre-cancellation of CFO is for the relay to estimate and correct w_{SR} (the source-relay CFO) in the first time slot, then apply the opposite frequency shift to its own transmission. Ideally this will result in a relay transmission whose carrier frequency exactly matches that of the source. This way the destination doesnt observe the CFO due to any intermediate nodes and observes it as if a single two/three-antenna node had transmitted two/three waveforms [5]. The carrier frequency at the relays will be given now be given as

$$f'_{R1} = f_{R1} + \Delta f_{SR1} \tag{21}$$

$$f'_{R2} = f_{R2} + \Delta f_{SR2} \tag{22}$$

Now the problem has boiled down to a single CFO estimation and we make use of algorithm in [1]

1) Coarse Frequency Offset Estimation and Compensation: The coarse CFO estimation is done during L-STFs by finding the auto-correlation between two received short training symbols [1] as given in equation .

$$\theta_c = angle\{\sum_{q=0}^{N_{STF}-1}\sum_{n=0}^{L_{STF}-1} r^*[n]r[n+N]\} \tag{23}$$

L_{STF} is the STF window length equal to 16. N_{STF} is the number of STFs used for averaging.

$$\hat{\epsilon}_{cf} = \frac{\theta_c}{2\pi N_{cp}} \tag{24}$$

Coarse CFO Correction is applied on the received samples by multiplying the receiver input samples with the phase of $-2\pi\hat{\epsilon}_{cf}$.

2) Fine Frequency Offset Estimation and Compensation: The coarse CFO estimation is done during L-LTFs by finding the auto-correlation between two received long training symbols using the below equation.

$$\theta_f = angle\{\sum_{n=0}^{L_{LTF}-1} r^*[n]r[n+N]\} \tag{25}$$

L_{LTF} is the LTF window length equal to 64.

$$\hat{\epsilon}_{ff} = \frac{\theta_c}{2\pi L_{LTF}} \tag{26}$$

Fine CFO Correction is applied on the received samples by multiplying the receiver input samples with the phase of $-2\pi\hat{\epsilon}_{ff}$ using the equation

$$r[n] = r[n] * exp\{-j2\pi\hat{\epsilon}_{ff}\} \tag{27}$$

IV. Performance Evaluation

In this section, we evaluate the performance of the system by Monte-Carlo simulations. We use two standard 3G channel models [7] referred to as Pedestrian Channel A and Vehicular Channel A. A generalized exponential decaying multipath channel model is also considered which we refer as Exponential channel. The parameters of the system are summarized in Table II. The Relay nodes (R1 and R2)are relatively placed at half the source to destination distance according to which the received power at the destination varies.

Firstly, the performance of the timing and frequency synchronization algorithms under ideal and realistic channel conditions is presented. In simulations, we have assumed the timing offset of different transmitter nodes is distributed over [-3,3] samples and the frequency error of each node can take values between [-10,10] ppm which is equal to [-10,10]Khz at the carrier frequency. Channel estimation of used subcarriers for individual wireless links l are obtained by using the received LTF symbols (L1, L2 and L3) and performing least squares estimation in frequency domain. Phase tracking is performed on the pilot locations of the received signals to remove the phase rotation due to residual frequency offset.

TABLE II
SIMULATION PARAMETERS FOR COOPERATIVE OFDM SYSTEM

Parameter	Value
Total Bandwidth	2 MHz
Carrier Frequency	1 GHz
Subcarrier Frequency spacing	31.25 KHz
Total number of subcarriers (data+pilots+guard)	64(48+4+12)
Length of Cyclic Prefix	16 samples
OFDM symbol duration	40 μs
Number of used subcarriers in STF	12
Number of used subcarriers in LTF	52

Fig. 5 shows the probability of timing detection algorithm in all the three time slots under AWGN and realistic channels. It indicates that the probability of timing detection for frequency selective fading channels in TS3 reaches one and performs better at received SNRs lesser than 5dB. This is successively followed by TS2 and TS1 provided the received SNR is greater than 5dB. Also the algorithm works well in presence of multiple timing offsets added to presence of CFO.This is attributed to the use of proposed timing recovery at the relay and destination receivers.

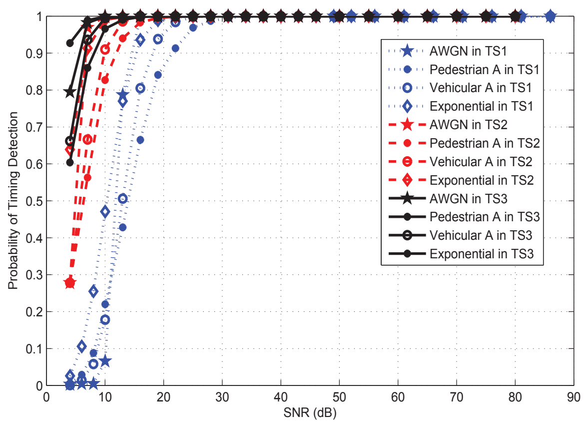

Fig. 5. Performance of Symbol timing algorithm in different time slots: Probability of correct timing detection

Fig. 6 shows the mean of normalized residual frequency errors at the end of coarse and fine frequency synchronization. The resulting frequency errors are shown in three time slots and under AWGN and fading channels. The results confirm that the residual frequency offset is significantly decreased in TS3 due to cooperation from three nodes i.e., Source, Relay1 and Relay2 followed by TS2 and TS1. Also these results embark the effectiveness of the frequency correction despite the presence of timing errors.

V. CONCLUSION

We have addressed the problem of timing and frequency synchronization in the relay based communication system. Frame structure is proposed to meet the space time relaying mechanism and also to deal with the synchronization issues when a node receives a superposition of multiple signals.

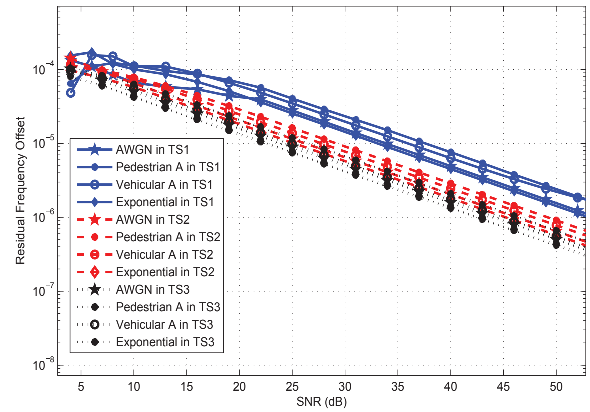

Fig. 6. Normalized Residual Frequency errors in different cooperation phases

The performance of the time synchronization algorithm is evaluated from the probability of correct timing detection and that of the carrier frequency synchronization algorithm is evaluated from the residual frequency offset. The results are presented for varied frequency selective channels for each of the three time slots and it is observed that the proposed algorithms can handle multiple timing and frequency offsets.

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