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Development of OFDM based Cooperative Communication System for Mitigation of Effect of Carrier Frequency offset

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ABSTRACT: In this paper, the effect of carrier frequency offset on a network where multiple independent devices cooperate to form virtual multiple input multiple output networks is analyzed. The common phase error and inter-carrier interference effect on cooperative Alamouti STC OFDM system due to carrier frequency offset is investigated and OFDM based cooperative communication system for mitigating the effect of carrier frequency offset is developed.

KEYWORDS: OFDM; MIMO; Frequency Offset; CPE; ICI; Cooperative Diversity; Cooperative Alamouti STC.

I. INTRODUCTION

Wireless communication is one of the most vibrant areas in the communication field today. It is used to transfer information over a distance without the use of a guided medium. Due to the sharply increasing in demand for wireless connectivity, it has developed extremely fast during the last two decades. However, wireless communication is not as reliable as guided medium communication, due to fading and other propagation effects. Accordingly, the techniques to improve its capacity and reliability become the key objective for current research. Numerous techniques have been proposed to enhance the performance and reduce the interference for wireless communication, such as Multiple-Input Multiple-Output (MIMO), Space-Time Codes (STCs) and Orthogonal Frequency Division Multiplexing (OFDM).

It is widely acknowledged that the combination of MIMO and STCs is able to provide a significant improvement of the capacity and bit error performance of wireless systems. However, there are some existing limitations of MIMO. For instance, transmitters/receivers may only be equipped with a single antenna due to their tiny physical size which does not facilitate the space of at least a half wavelength to install two uncorrelated transmit (Tx)/receive (Rx) antennas. Thus, cooperative communication technique has been introduced to allow single-antenna devices to cooperate and create a virtual (or distributed) MIMO system in such as a way that the STC and MIMO concepts can still be implemented.

OFDM is a technique to against the frequency-selective fading or narrowband interference in wireless communication, thus improving the system reliability. This technique allows data to be transmitted in parallel by modulating the data on a set of orthogonal sub-carriers. An analysis which could clearly point out when the application of cooperative communication to OFDM-based systems shall significantly improve the system bit error performance, compared to a SISO system, is highly desired.

Synchronization in OFDM systems has been the subject of much analysis [1; 3; 5; 6; 8; 9-12]. The commonly considered errors of symbol timing offset, sample rate offset, phase noise, and carrier frequency offset each present their own unique set of challenges. OFDM systems are particularly sensitive to errors in carrier frequency, a problem made worse by the high carrier frequencies and narrow sub-carrier spacing of many systems as well as the economic need to use low-cost oscillators [1; 3; 6; 11; 13]. WiMAX, for example, has a sub-carrier spacing of about 15 kHz and is licensed to operate at frequencies such as 3.5 GHz.

In a network where multiple independent devices cooperate to form virtual MIMO networks, however, it may not be possible to directly apply these traditional techniques. Consider two independent single antenna transmitters cooperating to form a virtual Alamouti space-time code (STC) OFDM system, as shown in Figure 1. Since each transmitter has its own independent clock, the received signal has two separate frequency offsets. In this scenario, even with perfect synchronization to one of the two transmitters, the receiver will still experience a frequency offset due to the second transmitter.

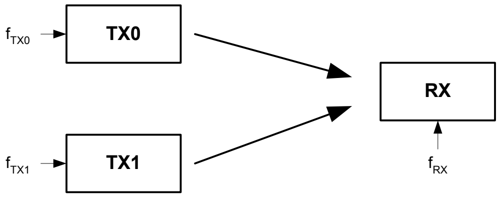

Figure 1: Cooperative Alamouti STC OFDM system.

In this paper we explore the effect of carrier frequency offset and then consider the case of a cooperative Alamouti STC OFDM system.

II. RELATED WORK

The primary effect of frequency offset is inter-carrier interference that leads to a reduction in SINR and ultimately to an irreducible error floor in performance was shown in [3]. As much effort has gone into quantifying the effects of carrier frequency offset, certainly more has been spent in mitigating its effects. [5], for instance, presents various such techniques.

The foundation of cooperative communication lies in the concept of relaying, introduced by [14]. Later on, information theoretic properties of relay channels have been studied in [15]. In these pioneering contributions, maximum achievable communication rate has been derived for a basic three terminal model, containing a source, a relay and a destination. The idea of user cooperation has been introduced by [16, 17] for uplink transmission that improves the capacity and lowers the outage probability for a given data rate. A cooperative protocol is designed where two cooperating partners listen to the broadcasted packet and retransmit the data for each other. This technique also helps in improving the diversity gain, as both transmitting nodes have uncorrelated channels with the destination. Later, [18] extended the concept of cooperation, by designing energy efficient multiple access protocols based on decode-and-forward (DF) and amplify-and-forward (AF) relaying modes. Significant gains in terms of outage probability as compared to direct link transmission has been illustrated in this work. In addition to fixed relaying modes, an outage probability analysis in [19] has been carried out for adaptive and incremental redundancy modes. Distributed channel codes are used at relaying nodes for improving the bit or block error rate in [20–22]. A number of interesting relaying strategies including repetition coding [23–25], space time cooperation [26], and space time coded cooperation [27] have been proposed and significant gain in terms of error performance, outage probability and power efficiency has been illustrated.

III. OVERVIEW OF ANALYSIS OF CARRIER FREQUENCY OFFSET

Carrier frequency offset has two primary effects on an OFDM system: common phase error (CPE) and inter-carrier interference (ICI). CPE is a rotation of the signal constellation and is termed "common" because it affects all sub-carriers equally and independently of both sub-carrier index and other sub-carriers in general. ICI is caused by a loss of sub-carrier orthogonality. Figure 2 illustrates the effect of frequency offset in OFDM in the frequency domain. With no offset, each sample point depends only on a single sub-carrier. Once an offset is introduced, orthogonality among the sub-carriers is lost. Not only is the amplitude of the sub-carrier of interest slightly reduced, but other sub-carriers contribute significantly to the sample point, greatly reducing the CINR. Both CPE and ICI can be seen in Figure 3. Here the signal has a 40dB SNR but a +/-3% frequency offset that causes rotation of the constellations as well as a reduction in SINR (as evidenced by the spread of each constellation point). Figure 4 is included for reference: with a 40dB SNR and no frequency offset, the constellation is very clean.

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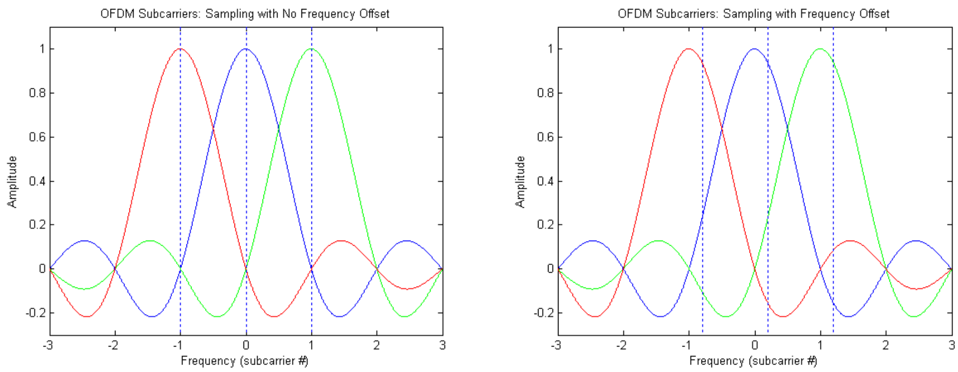

Figure 2: Illustration of effect of frequency offset.

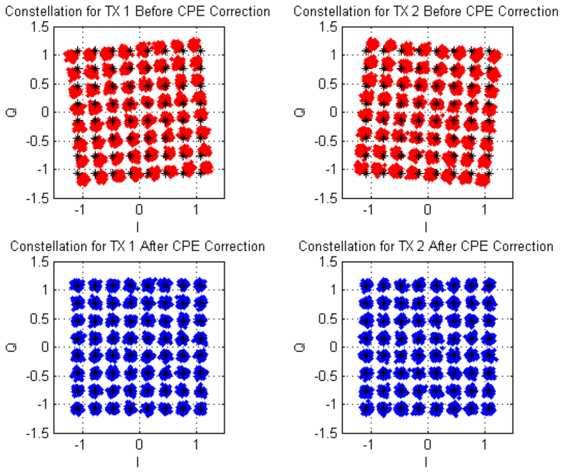

Figure 3: Constellations of Alamouti STC OFDM system with +/-3% frequency offset, 64-QAM, 40dB SNR in AWGN, before and after CPE correction. Black stars are original encoded constellation points.

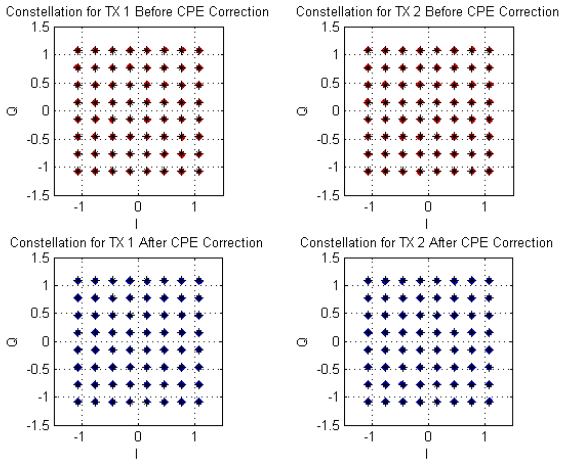

Figure 4: Constellations of Alamouti STC OFDM system with no frequency offset, 64-QAM, 40dB SNR in AWGN, before and after CPE correction. Black stars are original encoded constellation points.

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Many studies, including [1; 9; 12], have investigated methods to correct OFDM ICI, but these techniques are beyond the scope of this paper.

As shown in [10] and [1], analysis of a received OFDM signal with frequency offset reveals these two effects. Given a sequence of N data symbols $X[k]$, OFDM symbol time T_s, frequency error f_{err} in Hz, and phase offset ϕ, we represent the transmitted OFDM waveform in discrete time as

$$s[n] = \sum_{k=0}^{N-1} X[k] e^{j(2\pi(k+f_{err}T_s)n/N+\phi)},\ 0 \le n \le N-1 \tag{1}$$

The signal $s[n]$ is transmitted through a channel with impulse response $h[n]$. At the receiver, additive white Gaussian noise (AWGN) $v[n]$ is added. We assume perfect time and phase synchronization. The resulting signal is then demodulated with a DFT, yielding

$$R[k] = \frac{1}{N}\sum_{n=0}^{N-1}\left(s[n] \otimes h[n] + v[n]\right) e^{-j(2\pi kn/N+\phi)} \tag{2}$$

To simplify analysis and separate the effects of fading from our investigation, we assume an AWGN channel where $h[n] = \delta[n]$. Then

$$R[k] = \left(\frac{1}{N}\sum_{n=0}^{N-1}\sum_{l=0}^{l=N-1} x[l] e^{j2\pi n(l+f_{err}T_s-k)/N}\right) + V[k] \tag{3}$$

The case where $l=k$ can be separated and $R[k]$ re-written as

$$R[k] = X[k]I[0] + I[k] + V[k] \tag{4}$$

Where $V[k]$ is AWGN.

Further simplification of (3) when $l=k$ yields the term $I[0]$:

$$\begin{aligned} I[0] &= \frac{1}{N}\sum_{n=0}^{N-1} e^{j2\pi n f_{err}T_s/N} \\ &= \frac{1}{N}\sum_{n=0}^{N-1}\left(e^{j2\pi f_{err}T_s/N}\right)^n \\ &= \frac{1}{N}\frac{1-\left(e^{j2\pi f_{err}T_s/N}\right)^N}{1-e^{j2\pi f_{err}T_s/N}}, \text{by geometric series expansion} \\ &= \frac{1}{N}\frac{e^{j\pi f_{err}T_s}\left(e^{-j\pi f_{err}T_s} - e^{j\pi f_{err}T_s}\right)}{e^{j\pi f_{err}T_s/N}\left(e^{-j\pi f_{err}T_s/N} - e^{j\pi f_{err}T_s/N}\right)} \\ &= \frac{1}{N}\frac{-j2\sin(\pi f_{err}T_s)}{-j2\sin(\pi f_{err}T_s/N)} e^{j\pi f_{err}T_s\left(1-\frac{1}{N}\right)}, \text{by Euler's formula} \end{aligned}$$

$$I[0] = \frac{\sin(\pi f_{err}T_s)}{N\sin(\pi f_{err}T_s/N)} e^{j\pi f_{err}T_s\left(1-\frac{1}{N}\right)} \tag{5}$$

Thus we find that the first term of (4) has no dependence on the other sub-carriers and is, in fact, constant across the sub-carriers. This term is the CPE. Note that $f_{err}T_s = f_{err}/\Delta f$, where Δf is the sub-carrier spacing, and is therefore frequency error normalized to the sub-carrier spacing. The magnitude of (5) for relatively small frequency errors is essentially 1, as shown in Figure 5, so the primary effect of the CPE is a phase rotation of $\pi f_{err}T_s(1\text{-}1/N)$ radians.

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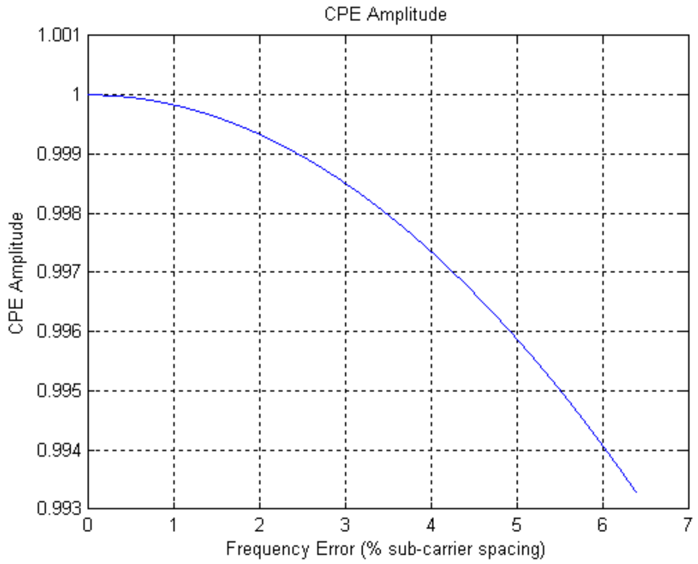

Figure 5: CPE amplitude as a function of percent frequency error.

The first term of (4) is not unique to OFDM systems. $X[k]I[0]$ would also be seen at the output of a matched filter in a single carrier system, yielding the same CPE. On the other hand, the second term of (4) is indeed a direct result of OFDM. It consists of the interfering contributions by all the other sub-carriers in the system. [1] writes this ICI term as

$$I[k] = \sum_{l=0, l\neq k}^{N-1} X[l] \frac{\sin\left(\pi(l + f_{err}T_s - k)\right)}{N\sin\left(\pi(l + f_{err}T_s - k)/N\right)} e^{j\pi(l+f_{err}T_s-k)\left(1-\frac{1}{N}\right)} \tag{6}$$

The degradation due to this ICI is approximated in [10] as

$$D(dB) \approx \frac{10}{3\ln 10}\left(\pi\frac{f_{err}}{\Delta f}\right)^2 \frac{E_s}{N_0} \tag{7}$$

Where Δf is the OFDM sub-carrier spacing in Hz, f_{err} is the frequency error (Hz), and E_s/N_0 is the linear SNR per symbol.

IV. Analysis of Cooperative Alamouti STC OFDM System

The Alamouti space-time code is a 2x1 transmit diversity scheme where, at symbol time n, antenna 1 transmits symbol S_1 and antenna 2 transmits symbol S_2 [2]. At symbol time n+1, antenna 1 transmits symbol $-S_2^*$ and antenna 2 transmits symbol S_1^*.

	Symbol Time n	Symbol Time n+1
Antenna 1	S_1-S_2^*	
Antenna 2	$S_2S_1^*$	

Thus the received signals are

$$Y[n] = H_1S_1 + H_2S_2$$
$$Y[n+1] = -H_1S_2^* + H_2S_1^* \tag{8}$$

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Where H_1 and H_2 are complex channel coefficients. The transmitted symbols can then be recovered, assuming perfect channel estimation:

$$\hat{S}_1 = H_1^* Y[n] + H_2 Y^*[n+1]$$
$$\hat{S}_2 = H_2^* Y[n] - H_1 Y^*[n+1] \tag{9}$$

For an OFDM system, we can simply apply the Alamouti STC scheme to each OFDM sub-carrier symbol independently.

V. Effect of CPE

In the case of cooperative communications, we have two independent sources of frequency offset, as illustrated in Figure 1. If we first consider the CPE, we find that we have a different CPE on each antenna due to the difference between the two transmitter frequencies and the receiver frequency:

	Symbol Time n	Symbol Time n+1
Antenna 1	$S_1 e^{j\theta_1}$	$-S_2^* e^{j\theta_1}$
Antenna 2	$S_2 e^{j\theta_2}$	$S_1^* e^{j\theta_2}$

$$Y[n] = H_1 S_1 e^{j\theta_1} + H_2 S_2 e^{j\theta_2}$$
$$Y[n+1] = -H_1 S_2^* e^{j\theta_1} + H_2 S_1^* e^{j\theta_2} \tag{10}$$

Standard Alamouti decode would yield the following recovered symbols:

$$\hat{S}_1 = H_1^* Y[n] + H_2 Y^*[n+1]$$
$$\hat{S}_2 = H_2^* Y[n] - H_1 Y^*[n+1] \tag{11}$$

Expanding each recovered symbol we find

$$\hat{S}_1 = S_1\left(|H_1|^2 e^{j\theta_1} + |H_2|^2 e^{-j\theta_2}\right) + S_2\left(H_1^* H_2 e^{j\theta_2} - H_1^* H_2 e^{-j\theta_1}\right)$$
$$\hat{S}_2 = S_2\left(|H_1|^2 e^{-j\theta_1} + |H_2|^2 e^{j\theta_2}\right) + S_1\left(H_1 H_2^* e^{j\theta_1} - H_1 H_2^* e^{-j\theta_2}\right) \tag{12}$$

Elimination of the CPE is traditionally performed with a single phase rotation. In this cooperative scenario, we see that this approach is non-optimal for all but the degenerate case where $\theta_1 = -\theta_2$. Instead, as found in [8], the optimal approach is to use two different CPE corrections, one per received symbol in time and introduced before Alamouti decoding:

$$\hat{S}_1 = H_1^* Y[n] e^{-j\theta_1} + H_2 Y^*[n+1] e^{j\theta_2}$$
$$\hat{S}_2 = H_2^* Y[n] e^{-j\theta_2} - H_1 Y^*[n+1] e^{j\theta_1} \tag{13}$$

We then find that the different CPEs have been eliminated from the recovered symbols:

$$\begin{aligned}
\hat{S}_1 &= S_1\left(|H_1|^2 e^{j(\theta_1-\theta_1)} + |H_2|^2 e^{j(\theta_2-\theta_2)}\right) + S_2\left(H_1^* H_2 e^{j(\theta_2-\theta_1)} - H_1^* H_2 e^{-j(\theta_2-\theta_1)}\right) \\
&= S_1\left(|H_1|^2 + |H_2|^2\right) \\
\hat{S}_2 &= S_2\left(|H_1|^2 e^{j(\theta_1-\theta_1)} + |H_2|^2 e^{j(\theta_2-\theta_2)}\right) + S_1\left(H_1 H_2^* e^{j(\theta_1-\theta_2)} - H_1 H_2^* e^{j(\theta_1-\theta_2)}\right) \\
&= S_2\left(|H_1|^2 + |H_2|^2\right)
\end{aligned} \tag{14}$$

Thus, with perfect channel and frequency offset knowledge, we can remove the effect of CPE from a cooperative Alamouti STC OFDM system.

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VI. EFFECT OF ICI

We find that the effect on a cooperative Alamouti STC OFDM system due to ICI is little different than that to a standard OFDM system. We still apply (7) but now have a contribution from each of our two frequency offsets.

We model a channel gain imbalance as a transmit power imbalance subject to a total power constraint P. For linear powers P_{TX1} and P_{TX2} transmitted from antennas 1 and 2, respectively, and power imbalance ΔP, we have:

$$P_{TX1} + P_{TX2} = P$$

Since $P_{TX1} = \Delta P P_{TX2}$, $\Delta P P_{TX2} + P_{TX2} = P$

Therefore

$$P_{TX1} = \frac{\Delta P}{1+\Delta P} P \text{ and } P_{TX2} = \frac{1}{1+\Delta P} P \quad (15)$$

We then have the total degradation in system performance given approximately by

$$D_{total}(dB) = D(f_{err1}, P_{TX1}) + D(f_{err2}, P_{TX2}) \quad (16)$$

For our system with two different frequency errors (f_{TX1}- f_{RX}) and (f_{TX2} - f_{RX}) and respective SNRs $P_{TX1}/(N_0B)$ and $P_{TX2}/(N_0B)$, we hypothesize that the optimal receiver frequency f_{RX} can be found by minimizing the sum of the individual degradations. Thus we set the derivative of the composite D_{total} to 0 and solve for f_{RX}:

$$D_{total}(dB) = \frac{10}{3\ln 10}\left(\pi \frac{f_{TX1} - f_{RX}}{\Delta f}\right)^2 \frac{P_{TX1}}{N_0 B} + \frac{10}{3\ln 10}\left(\pi \frac{f_{TX2} - f_{RX}}{\Delta f}\right)^2 \frac{P_{TX2}}{N_0 B}$$

$$= \frac{10\pi^2}{3\Delta f^2 \ln 10}\left(\begin{array}{l} \left(f_{TX1}{}^2 - 2 f_{TX1} f_{RX} + f_{RX}{}^2\right)\frac{P_{TX1}}{N_0 B} \\ + \left(f_{TX2}{}^2 - 2 f_{TX2} f_{RX} + f_{RX}{}^2\right)\frac{P_{TX2}}{N_0 B} \end{array} \right)$$

$$\frac{dD}{df_{RX}}(dB) = \frac{10\pi^2}{3\Delta f^2 \ln 10}\left(\left(-2 f_{TX1} + 2 f_{RX}\right)\frac{P_{TX1}}{N_0 B} + \left(-2 f_{TX2} + 2 f_{RX}\right)\frac{P_{TX2}}{N_0 B} \right) = 0$$

$$\left(-f_{TX1} + f_{RX}\right)P_{TX1} + \left(-f_{TX2} + f_{RX}\right)P_{TX2} = 0$$

$$f_{RX}\left(P_{TX1} + P_{TX2}\right) = f_{TX1}P_{TX1} + f_{TX2}P_{TX2}$$

$$f_{RX} = \frac{f_{TX1}P_{TX1}}{P_{TX1} + P_{TX2}} + \frac{f_{TX2}P_{TX2}}{P_{TX1} + P_{TX2}}$$

Substituting in (15),

$$f_{RX} = f_{TX1}\frac{\Delta P}{1+\Delta P} + f_{TX2}\frac{1}{1+\Delta P} \quad (17)$$

Note that (17) provides the optimal receiver frequency assuming perfect knowledge of the transmit frequencies and channel powers. Under these same assumptions, a traditional (non-cooperative) system would have no frequency offset, and therefore no CPE or ICI and no performance degradation. Even with perfect knowledge, the cooperative system will experience a loss in performance so long as $f_{TX1} \neq f_{TX2}$ (and ΔP ≠ 0, of course).

VII. SIMULATION OF COOPERATIVE ALAMOUTI STC OFDM SYSTEM

We simulate a cooperative Alamouti STC OFDM system in Matlab. To simplify the simulation, enable easier comparison with the analysis, and ensure that the effects of frequency error are not masked, we do not apply coding and we only consider an AWGN channel. Further, we assume perfect channel and carrier frequency estimates. It is again

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worth noting that, under similar assumptions, the traditional non-cooperative system would have no degradation in performance.

We take parameters from the WiMAX 802.16-2004 standard [7]: 4MHz bandwidth, 256 sub-carriers (200 data, 55 guard, 0 at DC), and 15.625 kHz sub-carrier spacing.

(A) General System Performance

Figure 6 shows basic BER performance with curves as expected from the analysis. With no frequency offset, the SISO and STC curves are the same and agree with the standard QAM BER formula [4, Eqn 6.23]. We note that we would only see diversity gain due to STC with a fading channel. With a frequency error of 1% of the sub-carrier spacing and equal STC branch power, we again see that curves for SISO, STC, and the performance degradation predicted by (7) and (16) all match. For STC, we set one transmitter to +1% frequency offset, the other transmitter to -1% frequency offset, and set the receiver to be the mean of the two transmit frequencies, which is the optimal setting for equal branch power, as given by (17). For purposes of comparison, we have intentionally not removed the 1% frequency offset in the SISO case, even though with perfect knowledge this removal would be possible. Finally, we show the effect of not correcting the CPE.

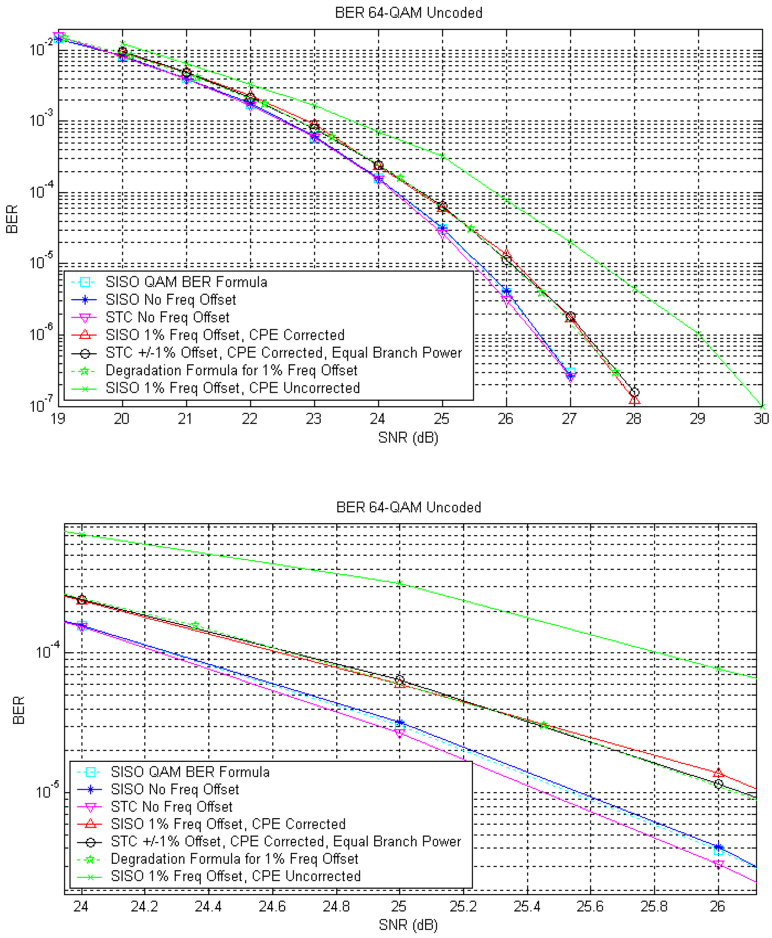

Figure 6: Top: BER performance for 64-QAM uncoded OFDM system. Bottom: zoom of top plot.

(B) Performance with Sub-optimal CPE Correction

Although, as discussed above, (13) can be used to optimally remove the CPE from a cooperative Alamouti STC OFDM system, it is interesting to observe system performance with the standard sub-optimal approach.

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Figure 7 shows a plot of BER against receiver frequency and (single, non-optimal) CPE correction angle. In this scenario we step through various branch power imbalances and leave the transmit frequencies at +1% and -1% offsets. We then try various combinations of f_{RX} and CPE angle. We observe that behavior is about as expected, with f_{RX} shifting toward the stronger transmit frequency. As the SNR imbalance increases, the system degenerates to a SISO system. f_{RX} approaches the dominant transmit frequency, the frequency error diminishes, and the CPE angle goes to 0.

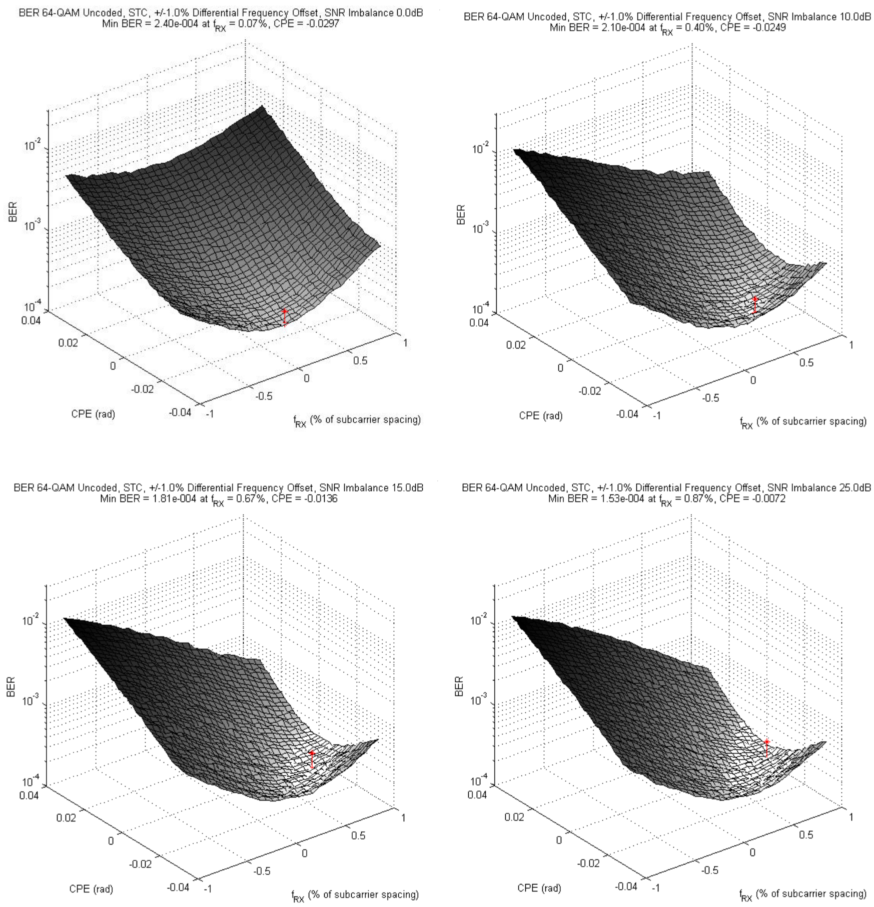

Figure 7: 3D BER showing measured optimal f_{RX} and CPE angle with increasing STC branch power imbalance.

Given sub-optimal CPE correction, we find that the optimal f_{RX} is no longer predicted by (17), as shown in Figure 8. This result is expected since system performance is now degraded by a loss of orthogonality between the two STC symbols. (17) is based on (7), which considers only degradation in performance due to OFDM ICI alone.

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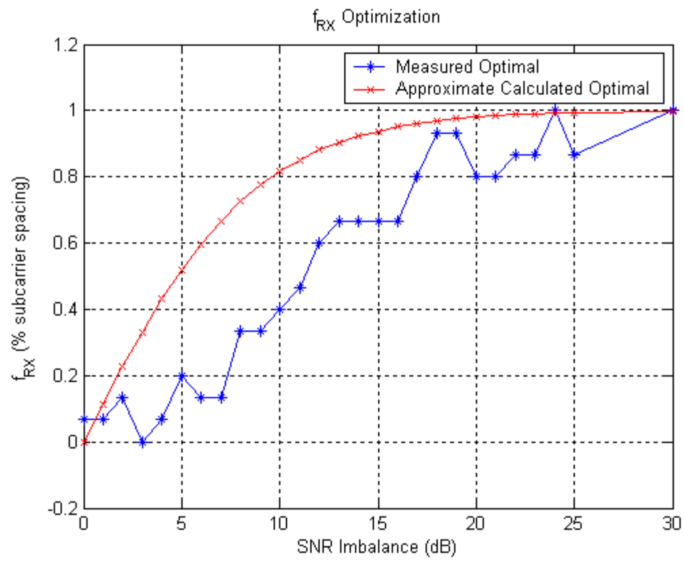

Figure 8: Optimal f_{RX} vs measured optimal with nonoptimal CPE correction.

For a given f_{RX}, we see in Figure 9 that the best single CPE we can choose is given by the argument of (5), with frequency error given by the difference between f_{RX} and the dominant transmit frequency.

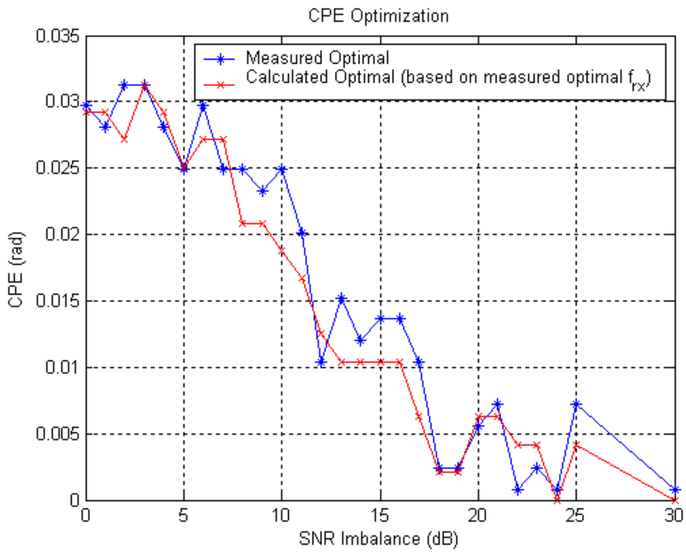

Figure 9: Best possible single CPE angle correction.

We see in Figure 10 the degeneration of the STC system (with frequency offset) to a SISO system with no frequency offset as the branch power imbalance increases. We note that these BERs are for AWGN and do not show the diversity gain that the STC system would experience (and would lose as it becomes a SISO system). The increase in BER between 0 and 5dB SNR imbalance is due to the non-optimal CPE correction causing a loss in orthogonality between the STC symbols. This degradation in performance is small.

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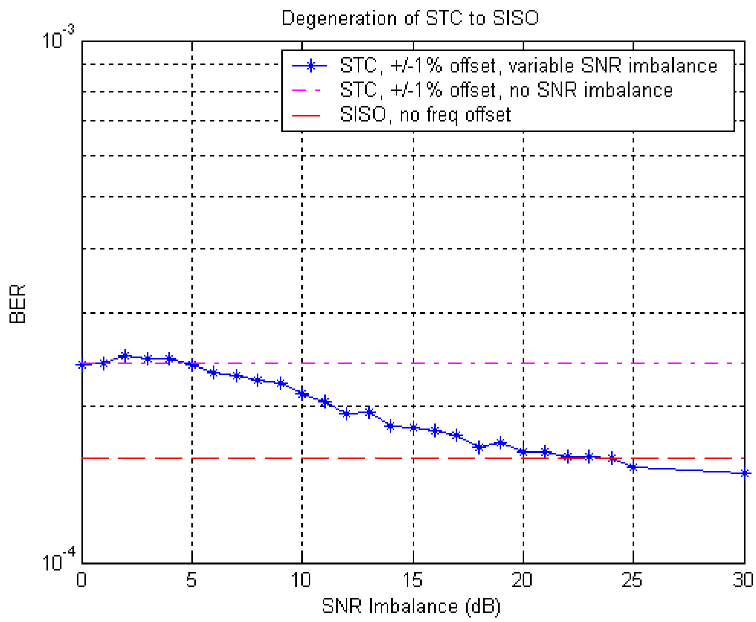

Figure 10: Degeneration of STC to SISO with increasing SNR imbalance.

Finally, we observe that even with sub-optimal CPE correction, performance degradation due to frequency offset is due primarily to OFDM ICI. Figure 11 shows that a single-carrier STC system with various amounts of SNR imbalance, a +/-1% frequency offset, and a single non-optimal CPE correction performs roughly the same as a system with no frequency offset at all.

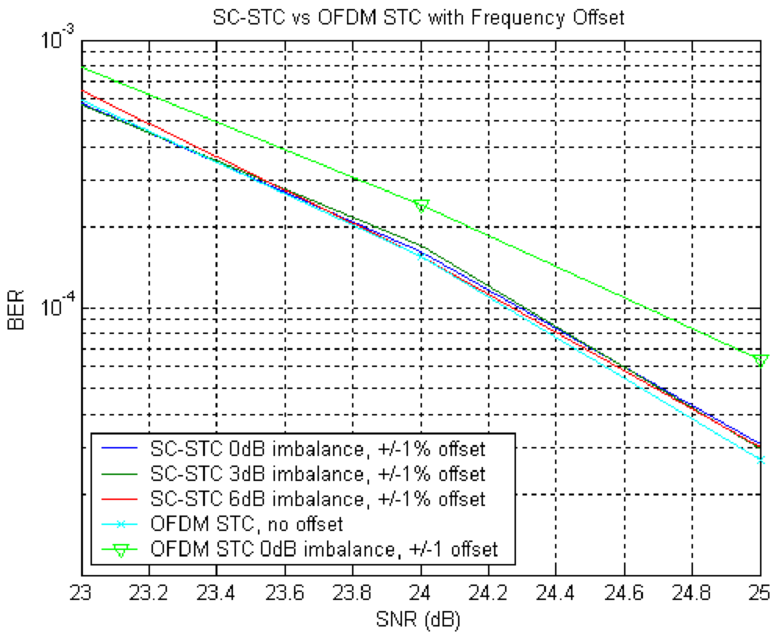

Figure 11: Single-carrier STC vs OFDM STC BER with +/-1% frequency offset.

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(C) Performance with Optimal CPE Correction

With optimal CPE correction given by (13), Figure 12, unlike Figure 8, shows a strong match between the predicted f_{RX} given by (17) and the measured optimal.

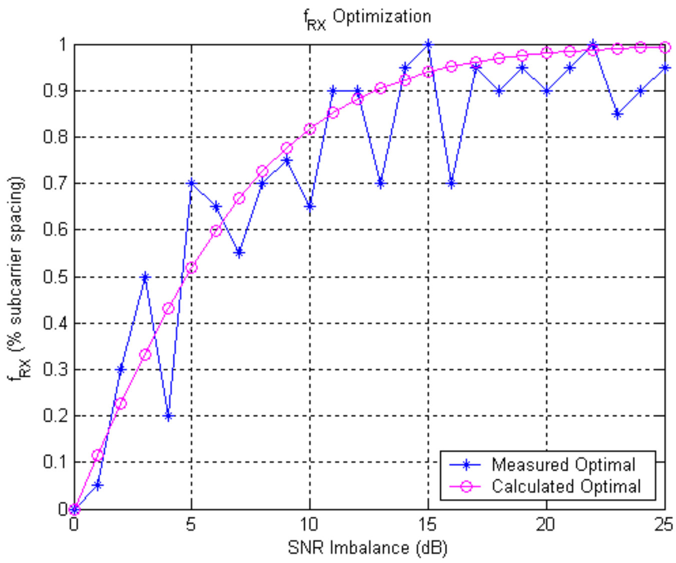

Figure 12: Optimal f_{RX} vs measured optimal with optimal CPE correction.

Further, the degeneration of STC to SISO in Figure 13, unlike in Figure 10, does not show any increase in BER between 0 and 5dB SNR imbalance, as there is no inter-STC symbol interference with optimal CPE correction. Figure 14 shows the degeneration of STC (with frequency offset) to SISO with no frequency offset on the standard BER vs SNR axes.

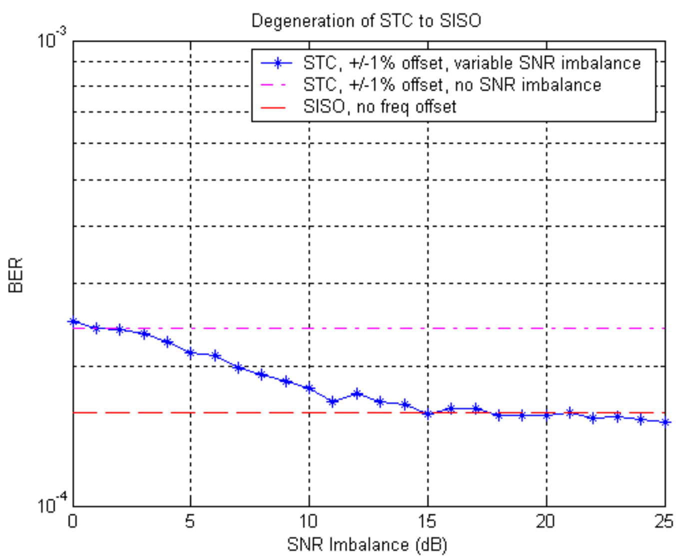

Figure 13: Degeneration of STC to SISO with increasing SNR imbalance.

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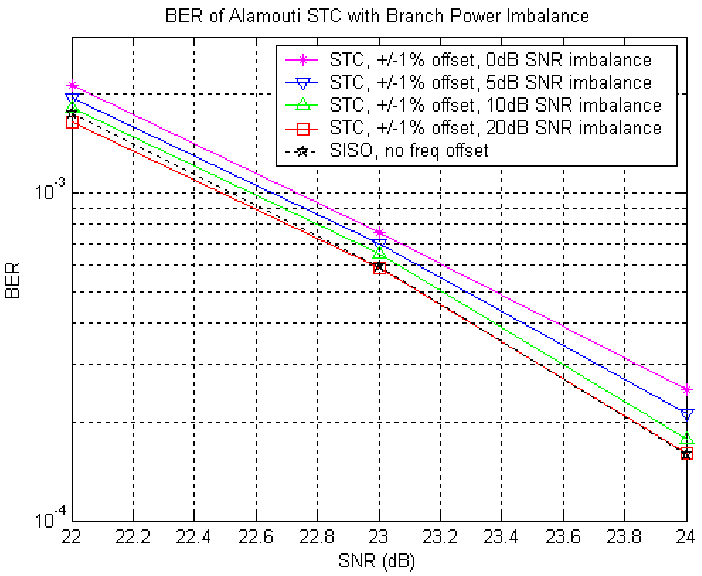

Figure 14: Degeneration of STC to SISO with increasing SNR imbalance.

VIII. CONCLUSIONS

We have shown that the primary effect of carrier frequency offset on a cooperative Alamouti STC OFDM system is OFDM ICI, a well-studied phenomenon with performance degradation given by (7) and (16). With perfect channel and frequency offset knowledge, we can completely eliminate the contribution due to CPE using (13). Unlike the non-cooperative SISO case, the receiver cannot eliminate the ICI even with perfect knowledge. However, the effect of ICI is no worse than that experienced by a regular SISO system with similar (albeit non-differential) frequency offset.

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