Performance of V-BLAST MIMO-OFDM Systems with Carrier Frequency Offset

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***Abstract*— In this paper we study the effects of carrier frequency offset (CFO) on the performance of a Vertical Bell Labs Layered Space-Time (V-BLAST) orthogonal frequency multiplexing (OFDM) system. It is shown that CFO introduced intercarrier interference (ICI) can cause significant performance degradation. ICI makes initial signal detection unreliable and introduces error propagation for the subsequent interference cancellation stages in the V-BLAST algorithm. An ICI cancellation method to improve the error performance is proposed which uses the initial data estimated. For the uncoded system used in the simulations, the technique is effective in reducing the symbol error rate at high signal-to-noise ratio values.**

I. INTRODUCTION

Rapid growth in communications and internet demands the use of reliable wireless links with large bandwidth capacity. A technique which promises high data rates is the *Vertical Bell Labs Layered Space-Time* (V-BLAST) architecture. Orthogonal frequency division multiplexing (OFDM) is robust against frequency selective fading and provides relatively simple receiver implementation. Hence the use of V-BLAST with OFDM leads to promising next generation wireless communication applications [1]–[3].

OFDM is sensitive to intercarrier interference (ICI) due to carrier frequency offset (CFO) and Doppler shift [4], [5]. CFO, the difference between the carrier and receiver local oscillator frequency introduce rotation for the useful signal and ICI, which cause loss of orthogonality among the demodulated OFDM subcarriers. ICI due to CFO causes significant bit error rates, low data throughput and has a negative impact on the system performance because it reduces the signal-to-interference-plus-noise ratio (SINR). Reference [6] presents an ICI analysis on MIMO-OFDM due to time varying characteristics of the channel and has shown that ICI is accentuated in the presence of multiple antennas. A limited analysis on the performance of a V-BLAST OFDM system with CFO was presented in [7] using a 6×4 antenna configuration. Most papers assume perfect frequency synchronization for V-BLAST signal detection and to our best knowledge the degradation issues have not been properly addressed so far.

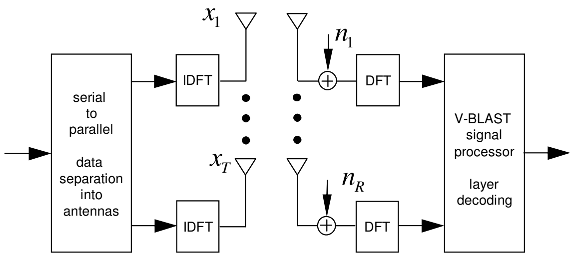
In this paper the performance of a V-BLAST OFDM system in the presence of CFO is considered. V-BLAST implements a successive interference canceling receiver, where the signal is spatially equalized on a layer basis. OFDM data symbols sent through *each* individual transmit antenna is referred to as a layer in the V-BLAST system. The decoding order optimizes the maximum post signal-to-noise ratio (SNR) for all layers and is crucial in controlling the error propagation throughout the layer detection process [8], [9]. The ICI due to CFO makes the signal estimation even more unreliable. We study the error propagation and the amount of CFO tolerable for a given symbol error rate (SER) by varying the normalized CFO. Although recent publications present design and implementation details on MIMO-OFDM systems [1], [10] much work still needs to be done on developing efficient synchronization algorithms. The analysis presented in this paper shows the necessity of such algorithms in order to implement high data throughput V-BLAST OFDM systems.

We also present details of a decision directed ICI cancellation technique. Initially estimated data symbols are used to subtract the ICI from the remaining data symbols.

The remainder of this paper is organized as follows. In Section II we present the V-BLAST OFDM system model. Section III presents an ICI analysis due to CFO and its impact on V-BLAST signal detection. ICI mitigation is discussed in Section IV and simulation results are presented in Section V. Finally Section VI concludes the paper with some remarks.

II. V-BLAST OFDM SYSTEM MODEL

We consider a V-BLAST OFDM system with T transmit and R receive antennas and assume perfect channel state information is available at the receiver. Transmit power is allocated uniformly throughout the



1: Block diagram of a V-BLAST OFDM transmission system.

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space-frequency grid. Fig. 1 shows the basic block diagram of a V-BLAST OFDM system. At the transmitter incoming bits are multiplexed to T transmit antennas, serial/parallel converted, mapped onto a modulation constellation. Following passing through an inverse discrete Fourier transform (IDFT) a cyclic prefix is inserted before upconverting to a radio frequency and transmitted to the channel.

Let $\mathbf{x}[n]$ denote the discrete time $T \times 1$ transmitted OFDM signal vector and $\mathbf{y}[n]$ be the received $R \times 1$ signal vector. We assume a wideband frequency selective channel. Hence the received signal $\mathbf{y}[n]$ can be expressed as

$$\mathbf{y}[n] = \sum_{p=0}^{P-1} \tilde{\mathbf{H}}_p \mathbf{x}[n-l] \tag{1}$$

where the complex $R \times T$ matrix $\tilde{\mathbf{H}}_p$ represents entries from the lth tap. $\tilde{\mathbf{H}}_p$ contains circularly symmetric Gaussian variables with zero mean and variance σ_p^2, where σ_p^2 is derived from the channel power delay profile. The entries within the matrix $\tilde{\mathbf{H}}_p$ can be correlated, however elements of $\tilde{\mathbf{H}}_p$ due to different propagation paths are assumed to be uncorrelated. The cyclic prefix length is assumed to be greater than the channel memory.

The received signal is converted to frequency domain using a DFT. Hence the decision symbol at the output of the DFT is given by

$$\mathbf{Y}(k) = \mathbf{H}(k)\mathbf{X}(k) + \mathbf{N}(k) \tag{2}$$

where $\mathbf{X}(k) = [X_k^{(0)}, X_k^{(1)}, \cdots, X_k^{(T-1)}]^t$, $X_k^{(i)}$ denotes the kth OFDM symbol transmitted from ith antenna, $(.)^t$ is the matrix transpose and $k = 0, 1, \cdots, N-1$. N is the total number of OFDM subcarriers and $\mathbf{N}(k)$ is the additive white Gaussian noise (AWGN) for the kth subcarrier with variance $E\left\{\mathbf{N}(k)\mathbf{N}^{\dagger}(k)\right\} = \sigma_n^2 \mathbf{I}_R$. $E(\cdot)$ is the expectation operator, $\mathbf{I}_R$ is the $R \times R$ identity matrix and $(\cdot)^{\dagger}$ is the conjugate transpose of a matrix. In (2), the frequency domain channel transfer function is written as

$$\mathbf{H}(k) = \sum_{p=0}^{P-1} \tilde{\mathbf{H}}_p \exp\left(\frac{j2\pi pk}{N}\right) \tag{3}$$

Note that from (2), OFDM converts the wideband MIMO channel into a set of N parallel narrow band channels. Hence the V-BLAST algorithm can now be applied per subcarrier basis [2]. V-BLAST uses a nonlinear detection scheme. The signal is multiplied with a filter matrix $\mathbf{G}$ and detected per layer basis. Assume that ith layer has the maximum SNR after linear interference cancellation. This is the layer where ith row of the matrix $\mathbf{G}$ has the minimum Euclidean norm. The symbol decision statistic in the ith layer can be expressed as,

$$\hat{\mathbf{X}} = \mathbf{G}\left(\mathbf{H}\mathbf{X} + \mathbf{N}\right) \tag{4}$$

For notational simplicity we have dropped subcarrier index k from (4). A zero forcing (ZF) based solution was reported in [9].

$$\mathbf{G} = \mathbf{G}_{\text{ZF}} = (\mathbf{H}^H \mathbf{H})^{-1} \mathbf{H}^H \tag{5}$$

Correct ordering of the layers is significant in controlling the error propagation throughout the detection process [11]. Initial detection stages will govern the overall performance that can be achieved with a V-BLAST OFDM system.

A. V-BLAST Detection Algorithm

The algorithm presented below [9] describes the V-BLAST detection steps.

Initialization:

$$i \leftarrow 1 \tag{6a}$$

$$\mathbf{Y}_1 = \mathbf{Y} \tag{6b}$$

$$\mathbf{G}_1 = (\mathbf{H})^+ \tag{6c}$$

$$k_1 = \text{arg min }_j \; ||(\mathbf{H}^+)_j|| \tag{6d}$$

Iteration:

$$\mathbf{W}_{k_i} = (\mathbf{G}_i)_{k_i} \tag{6e}$$

$$Z_{k_i} = \mathbf{W}_{k_i} \mathbf{Y}_i \tag{6f}$$

$$\hat{X}_{k_i} = Q(Z_{k_i}) \tag{6g}$$

$$\mathbf{Y}_{i+1} = \mathbf{Y}_i - \hat{X}_{k_i} [\mathbf{H}]_{k_i} \tag{6h}$$

$$\mathbf{G}_{i+1} = ([\mathbf{H}]_{\bar{k}_i})^+ \tag{6i}$$

$$k_{i+1} = \text{arg min }_{j \notin \{k_1, \ldots, k_i\}} \; ||(\mathbf{G}_{i+1})_j|| \tag{6j}$$

$$i \leftarrow i + 1 \tag{6k}$$

where notations $(\cdot)^+$, $\|\cdot\|$, $(\cdot)$ denote the pseudo inverse of a matrix, norm of a vector and jth row of a matrix. $[\cdot]_j$ is the jth column of a matrix, $Q(\cdot)$ is the estimation operation, $\hat{x}$ is the decision on x and $[\cdot]_{\bar{k}_i}$ is the matrix generated by nulling the column k_i.

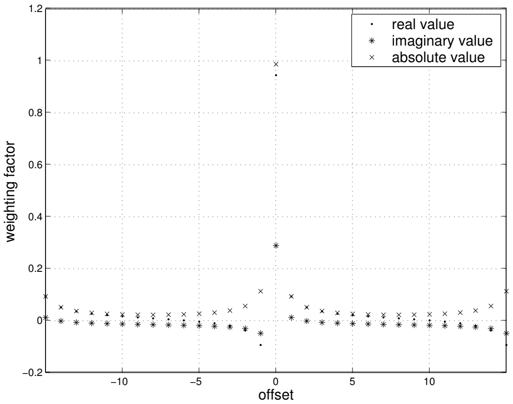
III. EFFECT OF CFO ON V-BLAST DETECTION

The received OFDM signal for the kth subcarrier after DFT processing in the presence of CFO $(T = R = 1)$ is given by,

$$\begin{aligned} Y(k) &= \frac{1}{N} \sum_{n=0}^{N-1} y(n) e^{\frac{-j2\pi kn}{N}} + N(k) \qquad (7) \\ &= \frac{1}{N} \sum_{n=0}^{N-1} e^{\frac{j2\pi \epsilon n}{N}} \sum_{l=0}^{N-1} H(l) X(l) e^{\frac{2\pi(l-k)n}{N}} + N(k) \\ &= \frac{1}{N} \sum_{l=0}^{N-1} H(l) X(l) S(l-k) + N(k) \end{aligned}$$

Discrete time domain OFDM signal $y(n)$ is multiplied by the factor $e^{j2\pi n\epsilon/N}$ in (7) to represent the CFO effect. ICI coefficients $S(k)$ are given by,

$$S(k) = \frac{1}{N} \sum_{n=0}^{N-1} e^{\frac{j2\pi n\epsilon}{N}} . e^{\frac{-j2\pi kn}{N}} \tag{8}$$



2: Real, imaginary and absolute components of the complex weighting factors $S(k)$ for $N = 16$ and $\epsilon = 0.1$.

Eq. (7) can be rearranged as

$$Y(k) = S(0)H(k)X(k) + \underbrace{\sum_{l=0,\, l\neq k}^{N-1} S(l-k)H(l)X(l)}_{\text{ICI}} + N(k) \tag{9}$$

An expression for $S(k)$ follows by summing the geometric series in (8).

$$S(k) = \frac{\sin \pi(k+\epsilon)}{N \sin\frac{\pi}{N}(k+\epsilon)} \exp\left[j\pi(1-\frac{1}{N})(k+\epsilon)\right] \tag{10}$$

and

$$S(0) = \frac{\text{sinc}(\epsilon)}{\text{sinc}(\epsilon/N)} \exp\left(j\pi(1-\frac{1}{N})\epsilon\right) \tag{11}$$

Modulated symbol for kth subcarrier is attenuated and rotated by the common phase error (CPE) $S(0)$. ICI is denoted by the second term in (9) which causes loss of orthogonality among the received subcarriers. The average SINR for the kth subcarrier, $\Psi(k)$ without CPE correction is given by

$$\Psi(k) = \frac{|H(k)X(k)S(0)|^2}{E\left\{\left|\sum_{l=0,\, l\neq k}^{N-1} S(l-k)H(l)X(l)\right|^2\right\}} \tag{12}$$

When SNR is high, the achievable system SER performance in the presence of CFO is governed by SINR.

Fig. 2 shows the ICI coefficients $S(k)$ for the case of $\epsilon = 0.1$ and $N = 16$. There are only N distinct coefficients as the values depend on the distance *mod N* between the subcarriers. Also note the rapid roll-off of the coefficients meaning that for a given kth subcarrier the ICI power is mostly concentrated on a few adjacent subcarriers. Hence only a small number of significant ICI terms will influence the subcarrier to be decoded [12].

In the case of T transmit and R receive antennas (9) can be easily modified.

$$\begin{aligned} \mathbf{Y}(k) &= \text{diag}\{S(0)\}\mathbf{H}(k)\mathbf{X}(k) \ \ \text{(signal)} \\ &+ \sum_{l=0, l\neq k}^{N-1} \text{diag}\{S(l-k)\}\mathbf{H}(l)\mathbf{X}(l) + \mathbf{N}(k) \ \text{(ICI)} \\ &= \text{diag}\{S(0)\}\mathbf{H}(k)\mathbf{X}(k) + \mathbf{Z}(l) + \mathbf{N}(k) \ \text{(noise)} \end{aligned} \tag{13}$$

where $\mathbf{S}(0)$ is a $R \times R$ diagonal matrix and $\mathbf{Y}(k)$ is the kth subcarrier received signal $R \times 1$ vector. $\mathbf{Y}(k) = [Y_k^{(1)}, Y_k^{(2)}, ..., Y_k^{(R)}]^t$. We have assumed that all receive antennas have the same CFO [1]. Equation (13) can be expressed in a simple matrix form by stacking all the received subcarrier signals.

$$\mathbf{Y} = \mathbf{S}\bar{\mathbf{H}}\mathbf{X} + \tilde{\mathbf{N}} \tag{14}$$

where $\mathbf{Y}$ given by $\mathbf{Y} = [\mathbf{Y}^t(0), \mathbf{Y}^t(1), ..., \mathbf{Y}^t(N-1)]$ is a $RN \times 1$ column vector, $\tilde{\mathbf{N}} = [\mathbf{N}^t(0), \mathbf{N}^t(1), ..., \mathbf{N}^t(N-1)]$ and $\bar{\mathbf{H}}$ is a $NR \times NT$ block diagonal matrix.

$$\bar{\mathbf{H}} = \text{diag}\{\mathbf{H}(k)\} \tag{15}$$

and $\mathbf{S}$ is given by

$$\mathbf{S} = \begin{pmatrix} \text{diag}\{S_0\} & \text{diag}\{S_1\} & \dots & \text{diag}\{S_{N-1}\} \\ \text{diag}\{S_{N-1}\} & \text{diag}\{S_0\} & \dots & \text{diag}\{S_{N-2}\} \\ \vdots & \vdots & \ddots & \vdots \\ \text{diag}\{S_1\} & \text{diag}\{S_2\} & \dots & \text{diag}\{S_0\} \end{pmatrix} \tag{16}$$

ICI term in (13) vanishes for perfect frequency synchronization (i.e., $\epsilon = 0$) and the matrix $\mathbf{S}$ equals $\mathbf{I}_{NR\times NR}$.

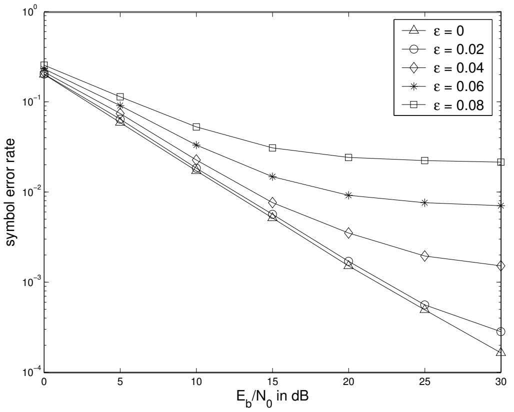
Note that in the presence of multiple antennas with CFO, $\mathbf{Y}(k)$ consists both of intercarrier and interantenna interference as denoted by the matrix $\mathbf{Z}(l)$. The covariance matrix of $\mathbf{Z}^{'}(l) = E[\mathbf{Z}(l)\mathbf{Z}^{\dagger}(l)]$ can be written as

$$E\left\{\sum_{\substack{m=0\\ l\neq k}}^{N-1} \sum_{\substack{l=0\\ l\neq k}}^{N-1} \Omega(m-k)\mathbf{H}(m)\mathbf{X}(m)\mathbf{X}^{\dagger}(l)\mathbf{H}^{\dagger}(l)\Omega^{\dagger}(l-k)\right\} \tag{17}$$

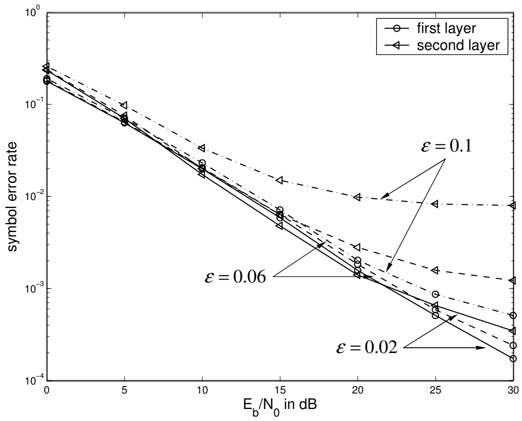
where $\Omega(m-k) = \text{diag}\{S(m-k)\}$ and $\mathbf{Z}^{'}(l)$ can be further simplified by following a similar approach to that of [6].

$$\sum_{\substack{m=0\\ l\neq k}}^{N-1} \sum_{\substack{l=0\\ l\neq k}}^{N-1} E[\Omega(m-k)\mathbf{H}(m)\sigma_{XX}\mathbf{H}^{\dagger}(l)\Omega^{\dagger}(l-k)] \tag{18}$$

In (18) $\sigma_{XX} = \text{diag}\{\sigma_1, \sigma_2, ..., \sigma_T\}$ are the eigenvalues of the matrix $E\{X(m)X^{\dagger}(l)\}$. Employment of multiple antennas increase ICI (due to CFO) compared to that of single-input single-output systems as seen from above analysis. This was also reported for the case of time varying channels in [6]. When the underlying MIMO channel is spatially correlated the effects of ICI can be more significant.



3: Symbol error rate versus E_b/N_0 for various ϵ. $N = 64$ and 4-QAM. CPE was not corrected.



4: Error propagation for layers detected first and second in a 2×2 V-BLAST OFDM system. CPE was corrected before decoding.

Effects of CFO for the BLAST detection algorithm can now be explained as follows. At the receiver detection is performed per subcarrier basis [1], [2]. As seen from (13) with CFO, $\mathbf{Y}(k)$ is affected by ICI in addition to AWGN and makes signal detection and nulling even more unreliable at the initial decoding stages. Significant error propagation can result through the subsequent interference cancellation steps causing severe SER degradation for the upper layers. Fig. 3 shows the SER performance against E_b/N_0 for different normalized CFO values in the case of a 2×2 V-BLAST OFDM system. CPE was not corrected. For comparison case where $\epsilon = 0$ is also shown. With increasing ϵ the total SER increases clearly showing the influence of ICI. At *high* SNR system performance curves exhibit an error floor.

Fig. 4 shows the error propagation results with different values of CFO. CPE was corrected before decoding. "First layer" shown in Fig. 4 is the layer decoded first after optimum re-ordering. Clearly high values of CFO cause the error rate probability for the first layer to increase. Note the *difference* between the error rates of the first and the second layer also increases for large ϵ. ICI has a significant impact on the error propagation across the layers. For high CFO values, the SER degradation in the top layers are severely governed by the errors in the initially decoded layer.

IV. ICI MITIGATION

In this section we investigate a possible low complexity ICI mitigation technique. The existing algorithm must be modified taking ICI into consideration when interference cancellation is performed. One can use a joint interantenna and intercarrier interference technique, however such a method is computationally intense in both the number of antennas and the number of subcarriers. Another approach is to consider the additional ICI term as an interference source and carry out a spatial domain ZF or minimum mean square error suppression [6].

Details of a technique based on decision directed symbol estimation and ICI cancellation is presented in the following. Note that ICI matrix is mostly diagonally dominant. This means that only few adjacent subcarriers will affect the detection for the subcarrier of interest. Hence we use the V-BLAST algorithm to detect the kth subcarrier symbols for all R layers. These *assumed* correct symbols are then subtracted from the adjacent $\mathbf{Y}(k)$s to reduce the ICI. It is expected that with perfect symbol nulling, detection process for the subsequent stages will improve compared to a technique without using estimation and nulling. For estimated symbol *feedback* we can use a scheme where data symbols are detected and subtracted immediately. Another possible approach is to initially estimate a block of data symbols followed by canceling the estimated ICI in parallel. This saves some computational complexity in the subtracting step. The following algorithm describes the iterative method.

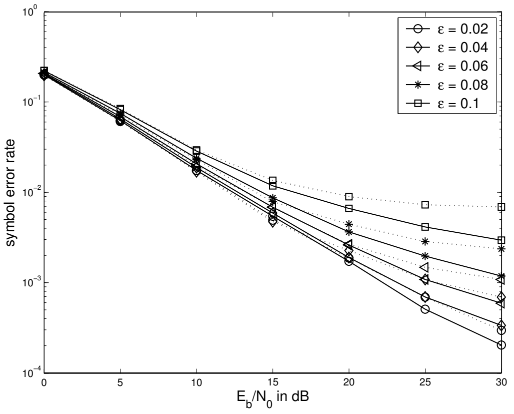
A. Decision Directed ICI Cancellation

Step 1: Partition the OFDM N subcarriers into a set of G groups.

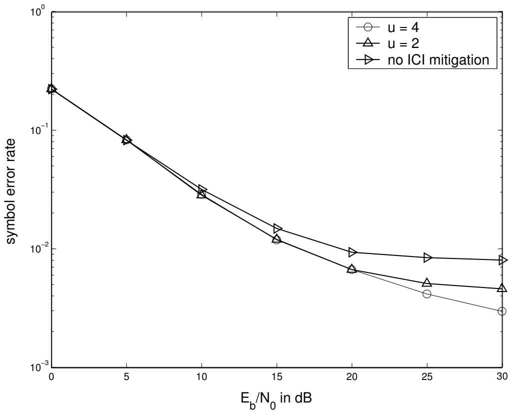
Step 2: For a group G, transmitted data in the kth subcarrier are detected using the V-BLAST algorithm.

Step 3: For the $(G + 1)$th group data estimation, in addition to conventional data detection and nulling the estimated ICI due to the previous groups are also canceled.

Note that if data symbols can be detected without errors at Gth group, then significant ICI for $(G{+}1)$th group can be perfectly subtracted. After all N subcarriers on the layers are detected further SER improvement can be obtained by subtracting estimated subcarriers in parallel. However for an uncoded system this approach may not be able to produce significant performance improvement due to error propagation across the layers and groups. In a coded V-BLAST system, ICI cancellation using this technique can promise better results as initial data estimates are more reliable. This has been the motivation



5: SER performance for the ICI mitigation method. CPE was corrected before decoding.



6: SER performance by varying the group size for a fixed $\epsilon = 0.1$. CPE was corrected before decoding.

of the work in [1] without the proposed ICI cancellation step.

V. SIMULATION RESULTS

We have considered an uncoded 2×2 V-BLAST OFDM system using 4-QAM modulation and $N = 64$. E_b/N_0 was defined to be $T/\log_2(M)\sigma_n^2$. Power delay profile of the channel is exponential and taps are uniformly distributed in OFDM sample spacing. Cyclic prefix length was set to 6 (in OFDM samples). The impulse response of the channel was assumed to be constant during one OFDM frame, and variant for different frames.

Fig. 5 shows the total SER performance against E_b/N_0 for various ϵ for the proposed ICI cancellation method. The dotted lines represent the result where no ICI mitigation was employed. Group size u was set to 4. The mitigation technique is effective in high SNR conditions where most of the initially detected signals are correct. When ϵ is small there is no clearly seen performance improvement with the proposed scheme. However when ϵ is large the mitigation method shows a better SER performance.

Fig. 6 shows the total SER performance for a fixed $\epsilon = 0.1$ with varying group sizes of 2 and 4. A larger group size means the ICI cancellation is effective if already detected OFDM subcarriers are correct. Simulation results not presented showed no performance improvement for group sizes greater than 4. This observation can be attributed due to two reasons. The uncoded system even at high SNR can produce detection errors and this can propagate in the ICI cancellation step. Another reason is that most of the significant ICI contributions are due to the neighboring subcarriers and subtracting further terms does not have an impact on the SER performance.

VI. CONCLUSIONS

We have analyzed the CFO errors and the resulting system degradation in a V-BLAST OFDM system. Symbol detection at symbol estimation and nulling steps becomes unreliable due to ICI. Hence error propagation in the V-BLAST algorithm can lead to poor system performance. For a 2×2 system simulation results showed that with CFO increasing the SER difference between layer detected first and second increases.

An ICI mitigation method was also proposed. Initial data estimated is subtracted in a decision directed way from the data to be decoded. Results showed that the proposed method is capable of mitigating ICI effects and thereby improving the system SER performance. For coded V-BLAST OFDM systems there exists a variety of decoding approaches to limit the ICI effects.

REFERENCES

[1] A. van Zelst and T. C. W. Schenk, “Implementation of a MIMO OFDM-based wireless LAN system,” *IEEE Trans. Signal Processing*, vol. 52, pp. 483-493, Feb. 2004.

[2] W. Yan, S. Sun and Z. Lei, “A low complexity VBLAST OFDM detection algorithm for wireless LAN systems,” *IEEE Commun. Lett.*, vol. 8, pp. 347-376, June 2004.

[3] K. B. Letaief, E. Choi, J. Y. Ahn and R. Chen, “Joint maximum likelihood detection and interference cancellation for MIMO/OFDM systems,” in *Proc. IEEE Vehicular Technol. Conf. (VTC 2003 Fall)*, Orlando, USA, Oct. 2003, pp. 612-616.

[4] J. Armstrong, “Analysis of new and existing methods of reducing intercarrier interference due to carrier frequency offset in OFDM,” *IEEE Trans. Commun.,* vol. 47, pp. 365-369, Mar. 1999.

[5] J. Armstrong, P. M. Grant and G. Povey, “Polynomial cancellation coding of OFDM to reduce the intercarrier interference due to Doppler spread,” in *Proc. IEEE GLOBECOM 98*, Sydney, Australia, Nov. 1998, pp. 2771-2776.

[6] A. Stamoulis, S. N. Diggavi and N. Al-Dhahir, “Intercarrier interference in MIMO OFDM,” *IEEE Trans. Signal Processing*, vol. 50, pp. 2451-2464, Oct. 2002.

[7] L. Wang, R. Ren and X. Shan, “Effect of carrier frequency offset on performance of BLAST-OFDM systems,” *IEE Electron. Lett.*, vol. 38, pp. 747-748, July 2002.

[8] A. Paulraj, R, Nabar and D. Gore, *Introduction to Space-Time Wireless Communications*. Cambridge, UK: Cambridge University Press, 2003.

[9] P. W. Wolniansky, G. J. Foschini, G. D. Golden and R. A. Valenzuela, “V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel,” in *Proc. Int. Symp. Signals, Systems and Electronics (ISSSE 98)*, Pisa, Italy, Sept. 1998, pp. 295-300.

[10] A. N. Mody and G. L. Stber, “Synchronization for MIMO OFDM systems,” in *Proc. IEEE GLOBECOM 2001*, San Antonio, TX, USA, Nov. 2001, pp. 509-513.

[11] B. Vucetic and J. Yuan, *Space-Time Coding*. Chichester, West Sussex, UK: Wiley, 2003.

[12] W. G. Jeon, K. H. Chang and Y. S. Cho, "An equalization technique for orthogonal frequency-division multiplexing systems in time-variant multipath channels," *IEEE Trans. Commun.*, vol. 47, pp. 27-32, Jan. 1999.