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High Data Rate MIMO-OFDM System using V-BLAST Architecture

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ABSTRACT

High date rate wireless systems with very small symbol periods usually face unacceptable Inter-Symbol Interference (ISI) originated from multipath propagation and their inherent delay spread. Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier-based technique for mitigating ISI to improve capacity in the wireless system with spectral efficiency (bps/Hz). On the other hand, Multiple -Input Multiple-Output (MIMO) systems have rising attention of the wireless academic community and industry because their promise to increase capacity and performance with acceptable BER proportionally with the number of antennas. Thus we have obtained better bit error rate using V-BLAST technique.

Keywords: ISI, OFDM,V-BLAST,BER and SNR

I. INTRODUCTION

OFDM applied to MIMO systems with V-BLAST signal processing at the receiver is a practical solution for Co -Channel Interference (CCI) between transmitted and received substreams of single -frame TDMA data. Recent technical literature has been reviewed to present some of the basic characteristics of MIMO-OFDM sytems analyzed in [3] that makes them attractive for high data-rate transmission over wireless channels, and the problems with the CCI associated to multi-user operation [2,6] which can reduce their performance. We present how the V-BLAST algorithm [7,8] implements a nonlinear detection technique based on spatial nulling process (ZF or MMSE approach to separate the transmitted independent substreams) combined with symbol cancellation to reduce CCI and to improve performance. We then discuss briefly the MIMO-OFDM system examined by [1] that implements V-BLAST CCI for multi-user operation (TDMA single-frame) to increase system capacity by increasing the substream data rate.

The analysis and simulation of the MIMO OFDM V-BLAST system for CCI cancellation is considered in two stages. The first stage involves the implementation of a system architecture model with vertical encoding, OFDM modulation-demodulation, V-BLAST signal processor with Zero Forcing (ZF) nulling for each OFDM subcarrier, and conventional decoding. The second stage compares the performance of the system for different antenna configurations and correlation factors between the MIMO channel components. The model simulation also compares MMSE nulling with the low-complexity sub-optimal ZF nulling at the receiver. Since variable-rate variable-power M-QAM adaptation is also possible (but not detailed in this project) with perfect and instantaneous channel knowledge at the transmitter, this study contributes to further research by comparing the performance of the system with correlated channels in different M-QAM schemes.

II. METHODS AND MATERIAL

1. MIMO OFDM V-Blast Systems

A. Orthogonal Frequency Division Multiplexing (OFDM)

As applications move to higher and higher data rates over wireless channels, ISI becomes more of a problem. As the data rate increases in a multipath environment, the interference goes from being characterized as at fading to frequency selective fading (when delay spread t_d exceeds the bit time). The multipath components begin to interfere with later symbols, resulting in irreducible error floors. Many solutions exist to compensate for ISI, the most popular of which has up till recently been equalizers. As we move to higher data rates (i.e. > 1 Mbps), equalizer complexity grows to level of complexity where training time exceeds the coherence time of the channel.

An alternate solution is Multicarrier Modulation (MCM). In this technique, the channel is broken up into *L* subbands. *L* is defined such that the fading over each MCM subchannel becomes flat fading ($B_s < B_c$ = coherence bandwidth of the channel), thus eliminating the problem of ISI. Frequency Division Multiplexing (FDM) is the simplest of these schemes. In essence, FDM divides the channel bandwidth into subchannels and transmits multiple relatively low rate signals by carrying each signal on a separate carrier frequency. To facilitate separation of the signals at the receiver, the carrier frequencies are spaced sufficiently far apart so that signal spectra do not overlap. Further, in order to separate the signals with readily sizeable filters, empty spectral regions are placed between the signals. As such, the resulting spectral efficiency of the system is quite low.

In order to solve the bandwidth efficiency problem, Orthogonal Frequency Division Multiplexing (OFDM) was proposed, which employs orthogonal tones to modulate the signals. The tones are spaced at frequency intervals equal to the symbol rate and are capable of separation at the receiver. This carrier spacing provides optimum spectral efficiency. It has been found that the OFDM symbols can actually overlap in the frequency domain and still be separated at the receiver. This is the advantage of OFDM over FDM. If each symbol has a bandwidth of *2B*, a FDM system will require a bandwidth of *2LB*, while OFDM will only require a bandwidth of *LB*. This property stems from the fact that symbols are orthogonal over time rather than frequency. Although OFDM is robust to ISI, it is not immune to the effects of flat fading which can cause unacceptable performance degradation. Adaptive modulation and frequency water-filling (not included in the simulation) can mitigate the effects of that fading.

One of the main problems with this powerful technique has been the need for numerous oscillators at the transmitter and receiver. An elegant solution to this was found in the Fast-Fourier Transform (FFT). By simply performing an FFT on a signal, we can use a single oscillator at the transmitter and receiver. The main idea is that by passing a signal through an IFFT, we multiply each input by $e^{j2pnm/B}$, which is a sampledversion of $e^{j2pnmt/B}$. This corresponds to a frequency shift of*m/B*. While in the implementation without the FFT, we would need *L* modulators each having a distinct carrier frequency, f_i, with the FFT we can simply have one modulator at the carrier frequency, while each of the symbols placed into the IFFT will be offset by *m/B* in frequency. The output of the IFFT will be time-domain OFDM symbols corresponding to the input symbols in the frequency-domain.

The *cyclic extension* (also called guard interval or zero-padding) is added to an OFDM symbol in order to combat the effect of multipath. ISI is avoided between adjacent OFDM symbols by introducing a guard period in which the multipath components of the desired signal are allowed to die out, after which the next OFDM symbol is transmitted. A useful technique to help reduce the complexity of the receiver is to introduce a guard symbol during the guard period. Specifically, this guard symbol is chosen to be a prefix extension to each block. The reason for this is to convert the linear convolution of the signal and channel to a circular convolution and thereby causing the FFT of the circularly convolved signal and channel to simply be the product of their respective FFT's. However, in order for this technique to work, the guard interval should be greater than the channel delay spread. Thus, we see that the relative length of the cyclic extension depends on the ratio of the channel delay spread to the OFDM symbol duration.

B. Multiple-Input Multiple-Output V-BLAST System Model

Although various implementation architectures for Multiple-Input Multiple -Output (MIMO) systems have been introduced since the BLAST (Bell Laboratories lAyered Space-Time) system was proposed in [7] and [8], a variation of such system, V-BLAST still emerges as a promising architecture due to lower receiver complexity (V-BLAST receiver algorithm) and higher data rates in the case of large number of antennas. This report considers a V-BLAST system with *N* transmit and $M = N$ receive antennas.

At the transmitter, a single bit stream (TDMA frame, for example) is horizontally encoded (HE) and demultiplexed into N substreams, and each substream is mapped to a symbol by the same constellation $\boldsymbol{A}$ and sent to its respective transmit antenna. Since total transmit power E_s is preserved irrespective of the number of transmit antennas, there is no increase in the amount of interference caused to the other users or substreams. Thus, at each symbol time t, a transmitted signal vector of size N, $\mathbf{a}^t = [a_1^t,... ,a_N^t]^T$, is sent to thereceiver over a rich-scattering and quasi-static flat fading wireless channel. Each time sequence $\{a^t\}_j$, (j = 1,2,... ,N) isreferred to as a layer. Transmitter needs no information about the channel, which eliminates the need for fast feedback links.

C. V-BLAST Processing Algorithm and CCI cancellation

Theoretically, ML detection would be optimal for V-BLAST detection. However, it's too complex to implement. For example, in the case of 6 transmit antennas and 4-QAM modulation, a total of $4^6 = 4096$ comparisons would have tobe made for each transmitted symbol. Therefore, V-BLAST performs a non-linear detection that extracts data streams by a ZF (or MMSE) filter $\mathbf{w}(k)$ with ordered successive interference cancellation (OSIC). CoChannel Interference traditional approaches require nulling vector being orthogonal to N-1 rows of $\mathbf{H}$ whereas OSIC requires nulling vector being orthogonal to N-i undetected components per iteration i, and

1) Zero-Forcing (ZF) is the decorrelating receiver where $H^\dagger$ isMoore -Penrose pseudo inverse of H
$w(k) = H^\dagger = (H^* H)^{-1} H^*$

2) Minimum Mean-Square Error (MMSE) is the maximum SNR receiver $w(k) = [H^* H^T + (M)I_N)^{-1}]H^*$

Detection order depends on which subset of (M-i) rows $\mathbf{w}_{ki}$ should be constrained by; since each component of the signal uses the same constellation, the component with the smallest $_{ki}$ will dominate the error performance. At each symbol time, it first detects the "strongest" layer (in the sense of SNR = E_s/N_o at the receiver branch), then cancels the effect of this strongest layer from each of the received signals, and then proceeds to detect the "strongest" of the remaining layers, and so on [8]. It is assumed that the receiver perfectly knows the channel matrix $\mathbf{H}$, which can be accomplished by classical means of channel estimation, e.g. insertion of training bits in the transmitted TDMA frames.

A low-complexity sub-optimal algorithm for ZF V-BLAST detection consists of four recursive steps describe as follows:

1)Ordering: Determine the optimal detection ordercorresponds to choosing $\mathbf{w}_{ki}$ the row of $\mathbf{w}(k)$ with minimum Euclidian norm. $\mathbf{w}(k)$ is referred to as nulling matrix and $\mathbf{w}_{ki}$ as nulling vector.

2)Nulling: Use the nulling vector $\mathbf{w}_{ki}$ to null out all the“weaker” signals and obtain the “strongest” (high SNR) transmitted signal
$y_{ki} = \mathbf{w}_{ki}^T \mathbf{r}$

3)Slicing: The estimated value of the strongest transmitsignal is detected by slicing to the nearest value in the signal constellation $\boldsymbol{A}$.
$\hat{a}_{ki} = \arg \{\min \|a - y_{ki}\|^2\}$

4)Canceling: Since the strongest transmit signal has been detected (assume $\hat{a}_{ki} = a_{ki}$), its effect should be cancelled from the received signal vector to reduce the detection complexity for remaining transmit *Iteration*: $i = i + 1$, and return to step 1 (i = 1, … M-1)

2. System Model

This report describes, simulates and analyzes the system based on a MIMO OFDM with V-BLAST receiver for CCI cancellation presented in [1]. The system works in single -hop ad hoc networks and provides a wireless access for slowly moving users (about 1 m/s) in an indoor environment. The proposed system is a single - TDMA stream scheme (for multiuser operation) capable to handle rates ranging adaptively from 64 kbps to 100 Mbps after variable-rate adaptive modulation is implemented, according to the subcarrier SNR and target

BER. In that sense, the system can implement different modulation schemes (BPSK, QPSK, 16-QAM, 64-QAM) and parallel convolutional turbo code with rates 1/2, 2/3 and 3/4.

The MIMO OFDM V-BLAST system operates in the 17 GHz unlicensed frequency band with an available bandwidth of 200 MHz (17.1–17.3 GHz) that is divided into four 50 MHz-width channels not simultaneously selectable. OFDM with L = 128 subcarriers (frequency subchannels) is designed for each of these 50 MHz wide channels. The indoor coverage ranges from 5 m for non line-of-sight to 20 m for line-of sight (LOS).

The indoor environment is the ideal rich-scattering environment necessary by the V-BLAST processing to get CCI cancellation at the receiver. V-BLAST algorithm with OSIC processing implements a non-linear detection technique based on Zero Forcing (ZF) filtering comb ined with symbol cancellation to improve the performance. The idea is to look at the signals from all the receive antennas simultaneously, first extracting the strongest sub-stream from the received signals, then proceeding with the remaining weaker signals, which are easier to recover once the strongest signals have been removed as a source of interference. Transmit space diversity techniques and V-BLAST receiver requires flat fading channel. The OFDM approach makes this assumption, for each frequency subchannel, reasonable.

A. Transmitter

The transmitter (Figure 1) has an array of N-antennas and performs a MIMO vertical encoding (VE). The first step is the encoding of the bit stream from the information source (TDMA frame for multiuser operation). The coded bits are then mapped to some symbols. It has been established that OFDM is a spectrally efficient modulation technique, thus spectral efficiency depends mainly on the bandwidth of the symbol, B_s. This depends on the modulation technique used to modulate the individual subcarriers. It is the mapping (over a constellation) that corresponds to the choice of modulation technique which should minimize B_s. M-QAM is the most spectrally efficient system and it is most often used in OFDM systems. The use of the IFFT does not pose a problem as it can take in both real and imaginary inputs of the QAM symbol.

Once the encoded bits are mapped to symbols, the symbol frame is passed through a demultiplexer (1? N) representing the space encoding. It maps symbols on the N space channels, which are substreams of the original frame. Each symbol substream is then put through a serial-to-parallel (S/P) converter which takes L of these symbols as input and produces L parallel output symbols corresponding to the OFDM sub-band channels. These symbols are put through the IFFT and then transmitted by the antenna n (n = 1, 2,… ,N). Because each input to IFFT corresponds to a OFDM subcarrier, at the output we get a time -domain OFDM symbol that corresponds to the input symbols in the frequency domain. In other words, the symbols constitute the frequency spectrum of the OFDM symbol. Once we have the OFDM symbol, a cyclic extension (with length depending on the channel) is performed. The final length of the extended OFDM signal will be the length of the original OFDM symbol plus the length of the channel response. As long as the guard interval, which is another name for the cyclic extension, is longer than the channel spread, the OFDM symbol will remain intact.

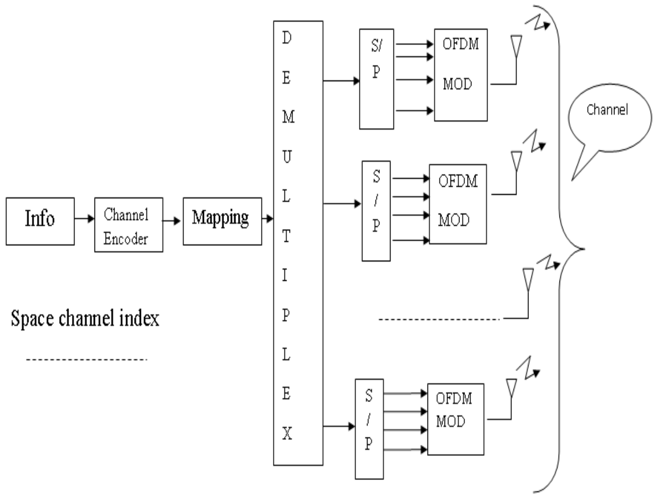

Figure 1. MIMO OFDM Transmitter

B. Receiver

After the channel, the cyclic extension is removed as it just contains the channel spread (assumed negligible in the simulation). Then the FFT is taken in each of the M receive antennas (V-BLAST requires $M \geq N$). Each antenna m receives a different noisy superimposition of the faded versions of the N transmitted signals (Figure 2). If the transmit and receive antennas are sufficiently spatially separated, more than λ/2 (at 17 GHz it is about 0.9 cm) and there is a sufficiently rich scattering propagation environment, the transmitted signals arriving at different receive antennas undergo uncorrelated fading. Moreover, if the channel state is perfectly known at the receiver, V-BLAST receiver is able to detect the N transmitted substreams.

The output of the OFDM demodulator, at the receive antenna m, is a set of L signals, one for each frequency subchannel, described by N

$$r_{m,l} = \Sigma\, h_{m,n,l} \cdot C_{n,l} + \eta_{m,l}, \text{ with } l = 1, \ldots, L, \; n = 1$$

where $h_{m,n,l}$ is the flat fading coefficient representing the channel from the transmit antenna n to the receive antenna m at frequency l, and $\eta_{m,l}$ are independent samples of a Gaussian random variable with power spectral density N_0 representing noise (where N_0 is the power spectral density of the noise at the receiver input).The M outputs for the frequency l are the inputs to a V-BLAST signal processor l. This sub-system is able to detect the N different space channels once flat fading is assumed (true because OFDM). This processing is repeated for each of the L sub-bands. The output of the L different V-BLAST signal processors is passed through a parallel-to-serial converter (with a multiplexer N? 1 is included) and the symbols are demapped and decoded to destination.

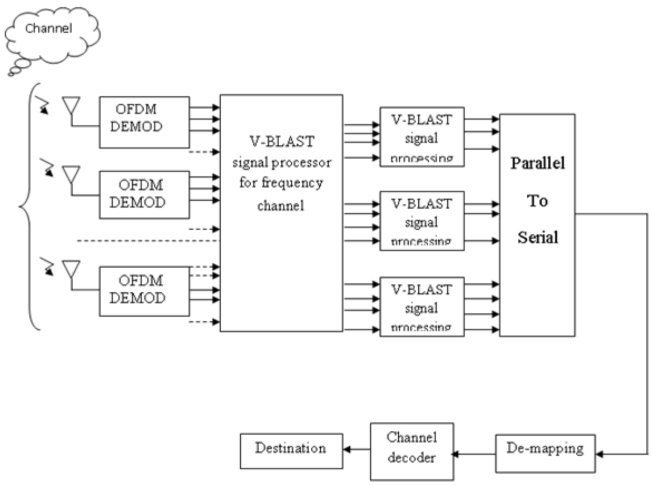

Figure 2 : MIMO OFDM Receivers

III. RESULTS AND DISCUSSION

A. Simulation

The simulation is of limited complexity. Interleaving and OFDM cyclic extension are not considered in this simulation (the latter because no delay spread between transmitter and receiver is assumed). The incoming bit stream is first encoded with conventional Hamming (n_h,k) with k =3 and n_h = 2^k-1. M_b-QAMgray-coded (to minimize the effect on bit error should a symbol error occur) constellation for bit to symbol mapping is implemented. Depending on M_b, many different constellations are possible, however for the purposes of this simulation only square constellations are considered and furthermore only constellations of size M_b = 2, 4 and 16 were simulated. The block time is defined as n_h*$\log_2(M_b)$ = 7*4 = 28 bit periods 16-QAM.

The output of the QAM modulator is then blocked further into a block of L=128 complex numbers, which represent the different subcarriers to be transmitted. These are put through an IFFT. The outputs of one symbol constitute an OFDM symbol.

Other parameters considered in the analysis and simulation of the MIMO OFDM V-BLAST was:

- Total radiated power E_s independent of N (E_s/N by each transmitter)
- ZMCSCG flat channel frequency response (delay spread is negligible) in each OFDM subcarrier
- Additive ZMCSCG noise with variance N_o is assumed (N_o is psd of the noise at the receiver branch)
- Slow changing channel (quasi-static during block time)
- Complex path gains hi,j are uncorrelated (?=0). Correlation in h_{ij} is also evaluated
- Rich scattering and adequate antenna spacing (= ?/2)
- Receiver perfectly knows the channel matrix **H** (no feedback for estimation of parameters in transmitter is required)
- Path delays for all spatial channels are the same and perfect symbol timing synchronization (for sampling) is assumed at the receiver. This is reasonable for co-located transmitters and receivers
- Same multipath-averaged SNR (E_s/ N_o) at any receiver branch for a given location
- Low complexity sub-optimal ZF V-BLAST detection. MMSE filtering is also evaluated.

As an addition, V-BLAST algorithm based in the QR factorization of **H** (**H** = **QR** where **R** is an upper triangular *MxM* matrix and **Q** is a *NxM* with **Q*Q** = **I**) with **w**(k) = **R** is also tested (see [9]).

B. Performance Analysis

A MIMO OFDM architecture that significantly increases the achievable bit rate of the system as well as decreases the CoChannel Interference has been studied and analyzed. Simulation results show the effectiveness of the considered system.

For ideal conditions (?=0) and same number of transmit and receive antennas, Figure 3 shows that V-BLAST technique for CCI cancellation increases the bit rate with number of antennas (ideally by *N*=*M*) without significantly worsening BER. The diversity level on ZF V-BLAST is *(M-N*+1) when detecting the first layer. With each layer detected, the diversity level of the resulting system should increase layer by layer, until *N* for the last layer, since the detected layers have been cancelled while the receive antennas still keeps constant. However, the diversity level of (*M*- *N*+1) for the first layer is too low in most cases, which largely limits the error performance of ZF V-BLAST. For example, if *N*=*M*, there would be no diversity gain for the first layer.

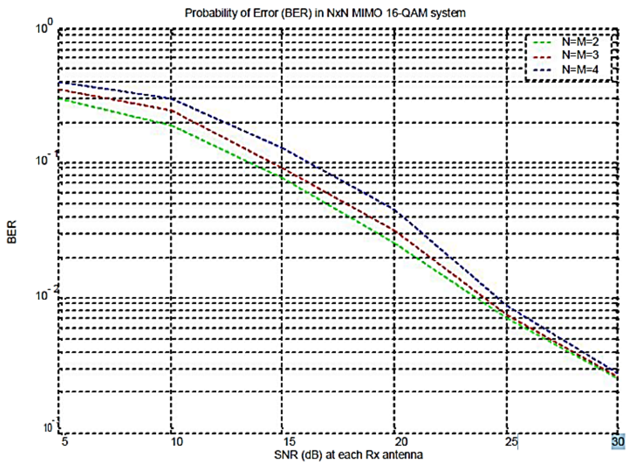

Figure 3. System performance comparison for different values of N = M.

MIMO systems with arrays of different number of receive antennas (*M* = *N* is required for V-BLAST) are showed in Figure 4. As can be seen, increasing M improves performance by order of *M-N*. This is because a greater number of received signals can be combined (diversity) in a more efficient way to obtain a more accurate estimate of the transmitted signals.

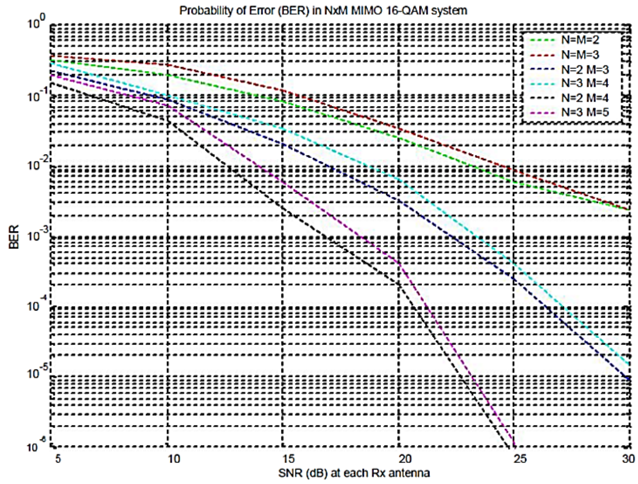

Figure 4. System performance comparison for different values of *M* – *N*

Several studies shown that if channel path gains of a (*N*,*M*) MIMO system are completely uncorrelated -even if channel is unknown for the transmitter-, the channel capacity scales linearly with *p*, where *p* = min{*N*,*M*}. However, in practical propagation conditions, these channel coefficients could be partially correlated. Generally the correlation coefficient (*?*) depend on many factors like the physical parameters of the transmit and receive antennas, i.e. antenna spacing, but also on the characteristics and the distribution of the scatterers. Figure 5 shows that when fades are correlated, the channel capacity can be significantly smaller (*?*?0) than when they are not (*?*=0), and Figures 6 and 7 suggests that the negative effect is more significant for higher modulation schemes.

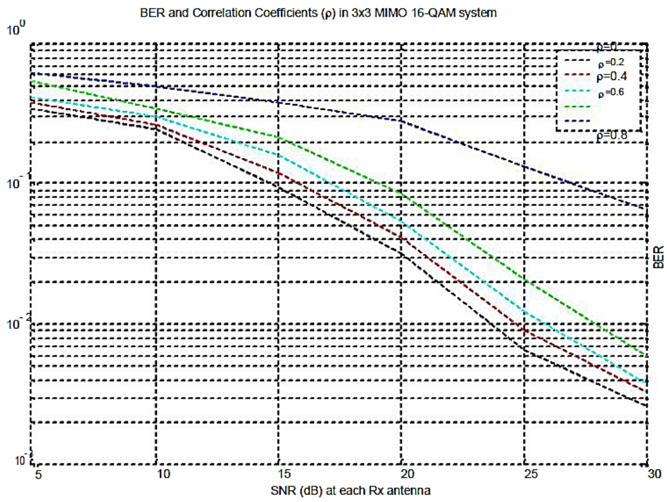

Figure 5. Performance of the 3x3 MIMO system for different correlation coefficients 16-QAM

Figure 5 also presents a nonlinear relation between BER degradation and correlation coefficients. As can also be seen, the negative effect of spatial correlation ? is larger at higher SNR. Under a threshold SNR, the BER is mainly limited by the noise. In general, channel capacity is smaller when paths are correlated. For MIMO 16-QAM 3x3 systems, the loss due to spatial correlation for ? = 0.6 is less than 5 dB. However, as can be seen, for ? > 0.6 the use of MIMO would be inefficient.

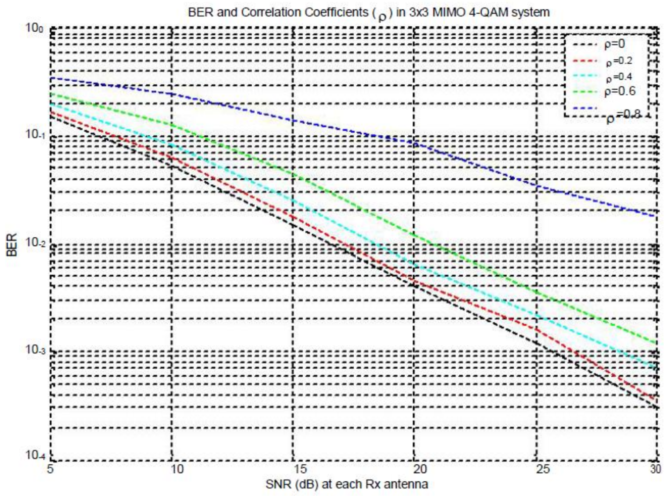

Figure 6. Performance of the 3x3 MIMO system for different correlation coefficients 4-QAM

Another interesting note is the fact that for 16-QAM, the BER does not seem to go down very far despite a high SNR. This is because for higher order QAM systems, there must be some channel inversion at the receiver to allow for proper decoding. This unfortunately amplifies the noise as well as the signal. The result with channel inversion at the output of the FFT is also shown above and it follows the same trend as the other modulation schemes shown in Figure 6 (4-QAM) and Figure 7 (16-QAM).

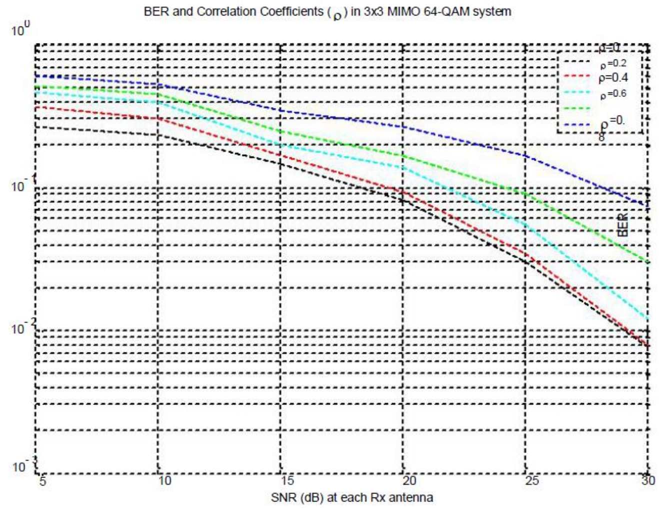

Figure 7. Performance of the 3x3 MIMO system for different correlation coefficients 64-QAM

One solution to improving nulling performance is to replace the ZF Nulling by the more powerful Minimum Mean Square Error (MMSE) Nulling, which improves the system performance over ZF V-BLAST by 6 dB at a bit error of 10^{2} for 3x3 MIMO as can be seen in Figure 8.

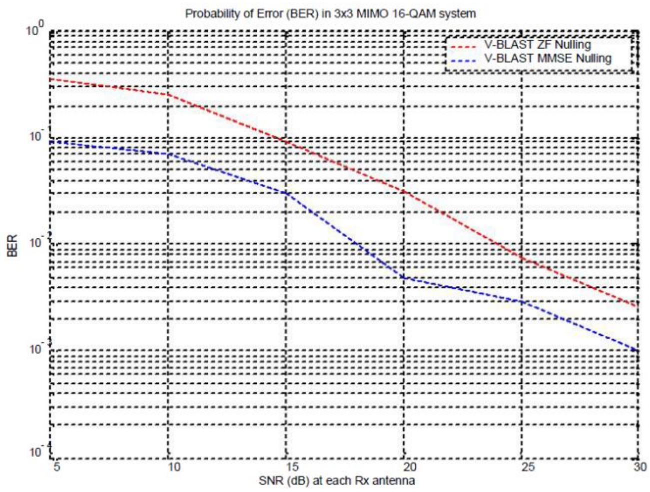

Figure 8. Performance of the 3x3 MIMO system for ZF and MMSE nulling

V-BLAST algorithm based in the QR factorization of **H** with **w**(k) = **R**, which can reduce the detection and CCI cancellation complexity in the receiver as presented in [9] and [10], was also tested with similar results to the "traditional" ZF V-BLAST processing (OSIC) for low SNR as can be seen in Figure 9. Additionally, trellis encoding (for 4-QAM) and Viterbi receiver were also superficially tested in this MIMO OFDM V-BLAST scheme. Both schemes showed a slightly better performance than Hamming (n,k) coding/encoding which would not justify the increase of complexity in the system.

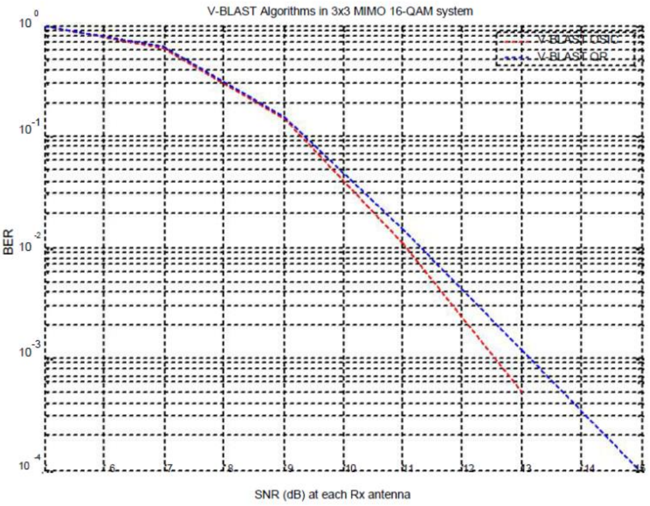

Figure 9. Comparison between ZF V-BLAST (OSIC) and QR algorithm

IV. CONCLUSION

This project has thoroughly analyzed the performance of the proposed MIMO OFDM V-BLAST system for different antenna configurations and propagation conditions. It has found that V-BLAST can get potentially higher spectral efficiency because no orthogonal transmitted signals and received co-channel signals are separated by decorrelation (processing algorithm) due to multipath.

The report has shown that MIMO OFDM V-BLAST systems are capable of improving bit rate without increasing total transmit power or required bandwidth with V-BLAST processing at the receiver as an efficient CCI cancellation technique.

Further research would describe the effect –under different array configurations and propagation conditions- of MMSE filtering in V-BLAST processing, Trellis encoding and Viterbi decoding, and variable -rate variable-power adaptive modulation schemes in the MIMO OFDM V-BLAST analyzed in this study. Thus we have obtained better bit error rate using V-BLAST technique as compared to all other techniques.

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