ENHANCED V-BLAST PERFORMANCE IN MIMO WIRELESS COMMUNICATION SYSTEMS

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ABSTRACT

Recently, a new detection algorithm for the Vertical Bell Laboratories Layered Space Time (V-BLAST) system, which we call Enhanced-V-BLAST, or simply E-V-BLAST, was proposed. V-BLAST has demonstrated very high spectral efficiency, there is a wide gap between the original V-BLAST algorithm and the Maximum Likelihood (ML) algorithm. Recently, some algorithms have been presented to make narrower this gap . In a new detection algorithm (Enhanced (E) -V BLAST) for V-BLAST system was presented which showed significantly better performance and flexibility than the original V-BLAST detection. The E-V-BLAST algorithm gets closer to the op- timum detection Maximum Likelihood (ML) algorithm by making decisions based on multiple symbols. The Enhanced (E)-V-BLAST has two parameters which can be adjusted to achieve a desired performance and complexity trade-off. In the present paper, we analyze the performance of EV-BLAST as a function of the two inherent adjustable parameters of E-V-BLAST. On the basis of this analysis, we obtain some useful characteristics of the E-V-BLAST algorithm which allow one to achieve the desired performance and complexity trade-off.

KEYWORDS: *E-V-BLAST algorithm, MIMO, Wireless Communication Systems.*

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The Vertical Bell Laboratories Layered Space Time (V-BLAST) system is a powerful detection algorithm for band-width efficient multiple antenna wireless communication sys-tem [2], [3], [4]. Although, V-BLAST has demonstrated very high spectral efficiency, there is a wide gap between the orig-inal V-BLAST algorithm and the Maximum Likelihood (ML) algorithm. Recently, some algorithms have been presented to make narrower this gap [1], [5], [7], [8], [9], [10]. In [1], a new detection algorithm (Enhanced (E) -V BLAST) for V-BLAST system was presented which showed significantly better performance and flexibility than the original V-BLAST detection. The E-V-BLAST algorithm gets closer to the op-timum detection Maximum Likelihood (ML) algorithm by making decisions based on multiple symbols. The Enhanced (E) - V-BLAST has two parameters which can be adjusted to achieve a desired performance and complexity trade-off. The main idea in E-V-BLAST is that, instead of making an immediate decision on a symbol being detected and cancelled at an iteration step, the decision about that symbol is made at a later level based on the multiple symbol possibilities that have accumulated by descending a tree of width S and depth T.

In what follows, we provide an analysis of the E-V-BLAST system. We analyze the performance of E-V-BLAST and compare the cases of various parameters which we can adjust for performance and complexity trade-off.

The remaining sections are organized as follows. In section II, we address the system model and overview original V-BLAST algorithm. In section III, we present E-V-BLAST algorithm which was introduced recently and analyze its performance. Some simulation studies are shown in section IV. We end in section V by presenting some conclusions.

SYSTEM MODEL

Let M denote the number of transmitting antennas and let N denote the number of receiving antennas in the wireless mul-tiple antenna communication system. The (M, N) single user system under consideration is depicted in Figure 1.

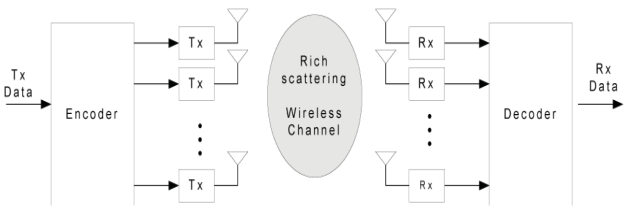


Fig. 1. Block diagram of V-BLAST system

Throughout this paper, we assume N = M for simplicity. It is assumed that there are considerable scattering takes place in the environment and that all the antennas are spaced for uncorrelated fading. We assume perfect channel state information at the receiver. The source stream is demultiplexed into M substreams, each transmitted from an antenna independently and simultaneously. The received signal r in complex baseband representation can be written as

$$r = Ha + \nu \quad (1)$$

where ν is a complex Gaussian noise vector with zero mean and variance σ^2_ν, a is transmitted signal vector and H is an $N \times M$ channel matrix whose elements are i.i.d complex Gaussian random variables with zero mean and unit variance.

ENHANCED V-BLAST ALGORITHM

The original V-BLAST embodies the simplest possible solutions. The Enhanced V-BLAST or simply E-V-BLAST algorithm gets closer to optimum detection by making decisions based on multiple symbols. In this section, we review the E-V-BLAST algorithm and conduct an approximate performance analysis. The idea of E-V-BLAST algorithm can be applied to any detection algorithm, detection using Pseudo inverse or QR decomposition. In this paper, we use Pseudo inverse detection for the explanation of E-V-BLAST.

A. E-V-BLAST algorithm

Optimum detection or Maximum Likelihood (ML) detection is computationally very expensive. So, in E-V-BLAST algorithm, we do the following two things.

1. In ead of ML detection of the signal based on all *M*, we make a symbol decision based on *T* (where $T \le M$), and continue iteratively.

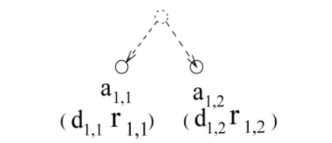
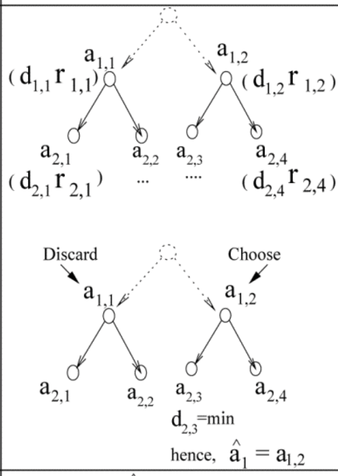
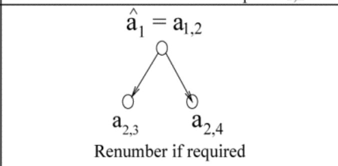
2. Instead of considering all the possible symbols of our constellation, we consider only the S best (nearest neighbors) symbols.

These two variables, *S* and *T*, are adjustable parameters of the algorithm. Their highest possible values are the total number of transmitters for *T* and the constellation size for *S*. In this case, detection will correspond to the ML case and will therefore have the highest possible computational complexity. In the simplest case (when $T = 1$, $S = 1$), the algorithm will be equivalent to original V-BLAST. When a decision is made, the best paths are kept and the rest are discarded.

The E-V-BLAST algorithm is explained with an example in Table 1 where we have initially assumed $T = 2$ and $S = 2$. By choosing $T = 2$ we delay every decision until the following recursion. The choice of S implies that decisions are made based on the combined distance of 2 different transmitter symbols. The two nearest symbols are chosen as shown in Figure 2. We call this operation "Multiple Slicing" and write it as $Q(y_1) = (a_{1,1}, a_{1,2})$, where $Q(y_1)$ denotes the slicing operation resulting in potential candidates $(a_{1,1}, a_{1,2})$. E-V-BLAST also use optimal ordering and DFE like conventional V-BLAST. To completely understand the algorithm, Table 1 should be followed.

Table 1

Example of detection with E-V-BLAST algorithm, S = 2, T = 2 [1]

Column 1	Column 2	Column 3
$r_1 = z_{1,1}a_1 + \nu_1$ • Form 2 potential candidates symbols (2 nearest neighbors) • Find distance metrics corresponding to each symbol • Find updated received vectors due to each, using symbol cancellation.		$y_1 = \mathbf{w}_1^T \mathbf{r}$ $(a_{1,1}, a_{1,2}) = Q(y_1)$ $d_{1,1} = \frac{\lvert y_1 - a_{1,1}\rvert^2}{\lVert \mathbf{w}_1^T \rVert^2}$ $d_{1,2} = \frac{\lvert y_1 - a_{1,2}\rvert^2}{\lVert \mathbf{w}_1^T \rVert^2}$ $\mathbf{r}_{1,1} = \mathbf{r} - a_{1,1}(\mathbf{H})_1$ $\mathbf{r}_{1,2} = \mathbf{r} - a_{1,2}(\mathbf{H})_1$
$r_2 = z_{2,1}\hat{a}_1 + z_{2,2}a_2 + \nu_2$ • Form total 4 potential candidates. Two assuming $a_1 = a_{1,1}$ and two assuming $a_1 = a_{1,2}$ • Find distance metrics for each new potential candidate. Parent node distances are incorporated in the child node distances. These distances are used for decision and pruning of tree. • Form updated received vectors due to each new statistic, using symbol cancellation. • Decision: Find node corresponding to minimum distance (say $a_{2,3}$). Parent of this node ($a_{1,2}$) is the final detected symbol for previous level (transmitter) • Discard undetected parent($a_{1,1}$) and its children		$y_{11} = \mathbf{w}_2^T \mathbf{r_{1,1}}$ $(a_{2,1}, a_{2,2}) = Q(y_{11})$ $d_{2,1} = \frac{\lvert y_1 - a_{1,1}\rvert^2}{\lVert \mathbf{w}_1^T \rVert^2} + \frac{\lvert y_{11} - a_{2,1}\rvert^2}{\lVert \mathbf{w}_2^T \rVert^2}$ $= d_{1,1} + \frac{\lvert y_{11} - a_{2,1}\rvert^2}{\lVert \mathbf{w}_2^T \rVert^2}$ $d_{2,2} = d_{1,1} + \frac{\lvert y_{11} - a_{2,2}\rvert^2}{\lVert \mathbf{w}_2^T \rVert^2}$ $\mathbf{r}_{2,1} = \mathbf{r_{1,1}} - a_{2,1}(\mathbf{H})_2$ $\mathbf{r}_{2,2} = \mathbf{r_{1,1}} - a_{2,2}(\mathbf{H})_2$ $y_{12} = \mathbf{w}_2^T \mathbf{r_{1,2}}$ etc. Similarly find $a_{2,3}, d_{2,3}, \mathbf{r}_{23}, a_{2,4}$ etc. if minimum distance $= d_{2,3}$ choose $\hat{a_1} = a_{1,2}$
$r_3 = z_{3,1}\hat{a}_1 + z_{3,2}\hat{a}_2 + z_{3,3}a_3 + \nu_2$ • After pruning, we have two potential candidates remaining for previous level. • Similar situation as in the beginning of row 2 above. • Rename, and continue recursively to detect all transmitter symbols.		Continue recursively, repeat steps above for new tentative symbols. Last symbol remaining at the end is detected based on its minimum distance.

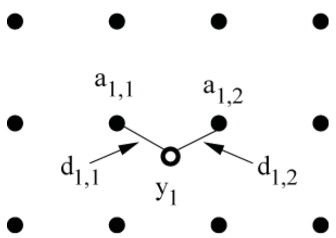


Fig. 2. Multiple Slicing: Choosing two possible candidates for a statistic

B. Approximate Performance Analysis of E-V-BLAST

In this subsection, we approximately analyze the performance of E-V-BLAST system. As we can see in the results of [5], all of signal errors are limited by the worst subchannel or performance of the first signal detection.

$$P[E_j] \leqslant P[E_1] \cdot \frac{1}{1-\epsilon}, \quad j = 2, 3, \cdots, M \tag{2}$$

where $\in$ is very small positive number for large SNR. This is because of inherent error propagation of Decision Feedback Equalization (DFE) in V-BLAST detection. Any detection error in the first signal will most likely result in detection errors of next signals. If we use feedforward matrix Q^H, the Hermitian of Q matrix after QR factorization, the elements of channel matrix will have different degree of freedom [5]. If we use pseudo inverse w^T_i, the post-detection SNR is changed [4]

$$SNR_i = \frac{< \lvert a_i \rvert^2 >}{\sigma_\nu^2 \lVert \mathbf{w}_i \rVert^2} \tag{3}$$

We carry out performance analysis of the first signal with i.i.d. Rayleigh fading channel and Additive White Gaussian Noise (AWGN). We use ZF (Zero Forcing)-V-BLAST, so we can regard all of interference is zero, when we detect the first signal of E-V-BLAST.

We define metric as

$$m(r_j, a_j; z_{j,j}) = -\lvert r_j - z_{j,j}\, a_j \rvert^2 \tag{4}$$

where $z_{j,j}$ is channel matrix component after ZF. We will use Pairwise Error probability (PEP) and union bound for analysis of performance. PEP is defined to be the probability of choosing the nearest signal of a_i, namely, $\hat{a}_i$, when a_i was transmitted. With perfect channel state information (CSI), PEP can be represented as

$$P_2(a_1 \to \hat{a}_1|z_{1,1}) = P[m(r_1, \hat{a}_1; z_{1,1}) \geq m(r_1, a_1; z_{1,1})] \quad (5)$$

If we use Chernoff bound for Q function

$$\begin{aligned} P_2(a_1 \to \hat{a}_1|z_{1,1}) &= Q\left(\sqrt{\frac{d_{min}^2 z_{1,1}^2}{4\sigma_\nu^2}}\right) \\ &\leq exp\left(-\frac{d_{min}^2 z_{1,1}^2}{8\sigma_\nu^2}\right) \end{aligned} \quad (6)$$

Where $d_{\min}^2 = |a_1 - \hat{a}_1|^2$. Averaging (6) with respect to $z_{1,1}$ yields

$$\begin{aligned} P_2(a_1 \to \hat{a}_1) &\leq E_{z_{1,1}}\left[exp\left(-\frac{d_{min}^2 z_{1,1}^2}{8\sigma_\nu^2}\right)\right] \\ &= \frac{1}{\left(1+\frac{d_{min}^2}{4\sigma_\nu^2}\right)} \end{aligned} \quad (7)$$

When applying union bound, we should separate error bound in two parts. One part is normal detection and the other part is the effect of E-V-BLAST algorithm.

$$\begin{aligned} P(E_1) &\leq \frac{M_c - S}{\left(1+\frac{d_{min}^2}{4\sigma_\nu^2}\right)} \\ &+ S \cdot P[m_T(\acute{\mathbf{r}}, \hat{\mathbf{a}}; \acute{\mathbf{Z}}) \geq m_T(\acute{\mathbf{r}}, \mathbf{a}; \acute{\mathbf{Z}})] \end{aligned} \quad (8)$$

where M_c is signal constellation size and $m_T(\acute{\mathbf{r}}, \mathbf{a}; \acute{\mathbf{Z}}) = -\sum_{j=1}^{T} |\acute{r}_j - \sum_{i=1}^{T} \acute{z}_{j,i} a_i|^2$

r_j' is assumed the received signal after relevant Zero Forcing(ZF) operation for performing ML detection with depth T . One of example of this kind of operation can be found in [5]. More specifically, when T = 2, we can represent Z´ as

$$\acute{\mathbf{Z}} = \begin{pmatrix} \acute{z}_{1,1} & \acute{z}_{1,2} & 0 & 0 & \dots & 0 \\ \acute{z}_{2,1} & \acute{z}_{2,2} & 0 & 0 & \dots & \vdots \\ \acute{z}_{3,1} & \acute{z}_{3,2} & \acute{z}_{3,3} & 0 & \dots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \ddots & 0 \\ \acute{z}_{M,1} & \dots & \dots & \dots & \acute{z}_{M,M-1} & \acute{z}_{M,M} \end{pmatrix} \quad (9)$$

Equation (8) will be clear, if we think about the algorithm.

We choose *S* signals and delay the decision of these signals in depth *T*. This means we choose some most error-prone signals *S* and apply modified ML detection with depth *T* for the error-prone signals.

The second part of (8) can be

$$\begin{aligned} &P\quad[m_T(\acute{\mathbf{r}}, \hat{\mathbf{a}}; \acute{\mathbf{Z}}) \geq m_T(\acute{\mathbf{r}}, \mathbf{a}; \acute{\mathbf{Z}})] \\ &\leq E_{\acute{\mathbf{Z}}}\left(\prod_{j=1}^{T} exp\left(-\frac{1}{8\sigma_\nu^2}\left|\sum_{i=1}^{T} \acute{z}_{j,i}(a_i - \hat{a}_i)\right|^2\right)\right) \\ &= \frac{1}{\prod_{j=1}^{T}\left(1+\frac{d_T^2}{4\sigma_\nu^2}\right)} \\ &= \frac{1}{\left(1+\frac{d_T^2}{4\sigma_\nu^2}\right)^T} \end{aligned}$$

where $d_T^2 = \sum_{i=1}^{T} |a_i - \hat{a}_i|^2$. (10)

Finally, we can express the error bound of E-V-BLAST as

$$P(E_1) \leq \frac{M_c - S}{\left(1+\frac{d_{min}^2}{4\sigma_\nu^2}\right)} + \frac{S}{\left(1+\frac{d_T^2}{4\sigma_\nu^2}\right)^T} \quad (11)$$

where $1 \leq S \leq M_c$ and $1 \leq T \leq M$. *S* and *T* are integers.

As we wrote above, the second part of (11) is a kind of ML detection. Therefore, basically what E-V-BLAST algorithm does is using modified ML detection or ML detection with depth *T* for some signal constellation which is most likely to be in error. According to the equation (11), we may ascertain some characteristics of E-V-BLAST. Increasing S means moving some of most error-prone signals in signal constellation from conventional V-BLAST detection to modified ML detection. Increasing *T* means improving the performance of modified ML detection part. Increasing *S* will show good performance at high SNR. But, the effect of increasing S will be reduced as *S* increased, because of signal constellation structure. The effect of increasing *T* will be reduced as SNR increases. Because at high SNR, the second term of equation (11) will be ignored, the error performance will be bounded at the first term of equation (11). As we can see, the first term of equation (11) is independent of *T*. So increasing *T* will not affect the error probability at high SNR. One more thing we should consider here is that in the highest complexity case ($S = M_c$, $T = M$), equation (11) becomes the usual ML detection.

SIMULATION RESULTS

The E-V-BLAST algorithm was tested by simulation using various *S* and *T* for a (5,5) uncoded system. Information symbols are modulated using 16QAM. According to the Figure 3, increasing *S* significantly improves the performance especially at high SNR. But, the effect of *S* is reduced as *S* is increased. This is because of signal constellation structure of QAM. Error usually occurs with right to the nearest neighbors. Increasing *S* covers the nearest neighbors step by step. So the effect of *S* is reduced as *S* is increased.

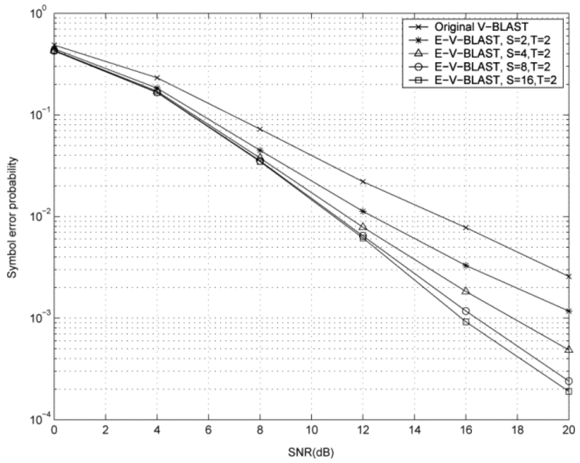


Fig. 3. Performance comparison of E-V-BLAST for increasing *S* and fixed *T*, uncoded (5, 5) 16 QAM

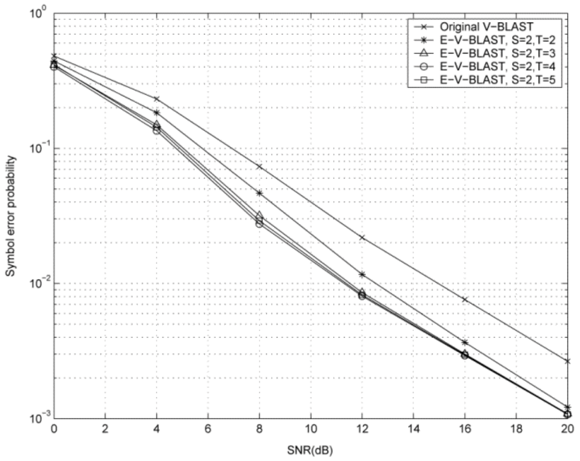


Fig. 4. Performance comparison of E-V-BLAST for increasing *T* and fixed *S*, uncoded (5, 5) 16 QAM

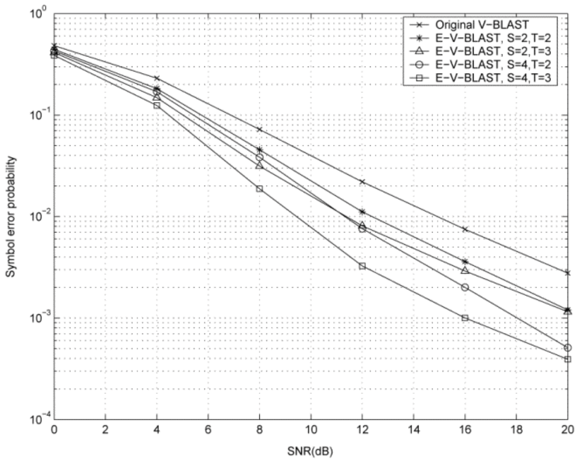


Fig. 5. Performance comparison of E-V-BLAST for increasing *T*, when *S* is changed, uncoded (5, 5) 16 QAM

Figure 4 shows at high SNR, the effect of *T* is not so significant. At high SNR, we can ignore the second term of (11), regardless of the value of *T*.

In this case, basically, the error probability (11) is bounded in the first term of (11). So all of the system performance of increasing *T*, but fixed *S* system will be same at the high SNR. The simulation of Figure 4 is the case of *S* = 2. If *S* is higher, then the effect of T will be increased, However, as shown in Figure 5, eventually, it also shows same behavior as mentioned above. These results induce us how we can reduce error probability efficiently.

CONCLUSION

We have presented performance analysis of E-V-BLAST and according to this analysis, we found some useful characteristics of the E-V-BLAST algorithm for performance and complexity trade-off. Increasing *S* is applying ML detection with depth *T* for some most error likely signals. Increasing *T* is improving the ML detection with depth *T*. Increasing T will not affect so much to the performance of E-V-BLAST at high SNR. The importance of increasing *T* depends on *S*. That is, the importance of increasing *T* depends on how many signals will be used for ML detection with depth *T*. Based on the analysis shown in this paper, we can use relevant level of *S* and *T*, depending on circumstances.

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