and the way in which they vary with modulation and with time is essential to enable robust and reliable performance of PCL systems.

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References

1 WILLIS, N.J.: 'Bistatic radar' (Artech House, 1991)
2 GRIFFITHS, H.D., and LONG, N.R.W.: 'Television-based bistatic radar', *IEE Proc. F*, 1986, **133**, (7), pp. 649–657
3 HOWLAND, P.E.: 'Target tracking using television-based bistatic radar', *IEE Proc., Radar Sonar Navig.*, 1999, **146**, (3)
4 BANIAK, J., BAKER, G., CUNNINGHAM, A.M., and MARTIN, L.: 'Silent Sentry passive surveillance', *Aviat. Week Space Technol.*, 7 June 1999
5 http://www.bbc.co.uk/reception/
6 WOODWARD, P.M.: 'Probability and information theory, with applications to radar' (Pergamon Press, 1953, reprinted by Artech House, 1980)

Detection algorithm improving V-BLAST performance over error propagation

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An iterative V-BLAST detection algorithm improving the performance over error propagation is proposed. In the algorithm, low-diversity substreams are iteratively decoded by using decisions from high-diversity substreams, and the performance is highly improved over the traditional one, which is demonstrated via simulations. Another advantage of this algorithm is that it is feasible to make a trade-off between performance and complexity.

Introduction: The Vertical Bell Laboratories Layered Space-Time (V-BLAST) system is a scheme that attains very high spectral efficiency while maintaining low implementation complexity [1]. However, in a practical V-BLAST system with a successive interference cancellation (SIC) detector the performance suffers great degradation due to the error propagation in its decision feedbacks. In the Letter, we propose an iterative approach to suppress error propagation and hence improve the performance in an uncoded case. For an (m, n) V-BLAST system, a single data stream is separated into m parallel substreams and then transmitted simultaneously, one on its corresponding transmit antenna. At the receiver, each antenna receives signals transmitted from all the m transmit antennas, and the optimal-ordered detection for each substream with interference nulling and SIC are performed. Specifically, the following discrete-time model is used:

$$\mathbf{r} = \mathbf{H} \cdot \mathbf{s} + \mathbf{n} \tag{1}$$

where $s = [s_0, s_1, \ldots, s_{m-1}]$ is an $m \times 1$ vector the jth component of which represents the signal transmitted from the jth antenna. The received signal and noise vector are both $n \times 1$ vectors, which are denoted by $\mathbf{r}$ and $\mathbf{n}$, respectively. The complex channel gain between the ith transmitter and the jth receiver is h_{ji}, for $i = 0, 1, \ldots, m-1$ and $j = 0, 1, \ldots, n-1$. $\mathbf{H}$ is modelled with i.i.d. $\tilde{N}(0, 1)$ entries, and $\mathbf{n}$ is the noise vector with i.i.d. $\tilde{N}(0, \sigma^2)$ entries. We assume that the channel is flat quasi-static, namely, the channel is considered as constant over a frame, but varies from one frame to another.

Problem analysis: In practical V-BLAST systems, error propagation is inevitable and it is responsible for performance degradation, which has been proposed and analysed in [2] and [3]. During the detection procedure, later-detected substreams are decoded through decision feedbacks from prior-detected ones. Under the assumption of no error propagation, the diversity degree of the next detected substream is supposed to increase by one after each cancellation. This means if no error propagation is considered, the next detected substream should get great benefit from the diversity increase, and hence its performance should be improved significantly. However, in practical systems the overall system performance is limited by the worst substream, which is the first detected one. It is because unreliable decision feedbacks from low-diversity substreams are used to decode high-diversity substreams that the overall performance is limited. Therefore, the worst substream is the bottleneck, and the significant gap between ideal and actual performance of substreams with high diversity degrees promises significant room for improvement. It is utilised in the following new algorithm.

Iterative detection algorithm: Since the first detection step is crucial for the overall performance, the diversity degree of this substream should be increased. Adding extra receive antennas will increase the diversity degree of the worst substream. However, in practice the number of receive antennas is limited by the size and feasible complexity of the mobile unit. Therefore it is not a practical solution. We present an iterative detection algorithm to effectively improve the diversity degree of the substreams detected antecedently, and hence improve the performance without adding more receive antennas. This algorithm decodes low-diversity substreams by using decisions from high-diversity substreams, which is just the reversed procedure of the traditional one. In this Section we give a detailed analysis of it.

We use a (4, 4) system as an example to explain our new algorithm. There are four substreams, denoted by c_1, c_2, c_3, c_4. The traditional V-BLAST decoding order [1] is $c_4 \rightarrow c_3 \rightarrow c_2 \rightarrow c_1$ (taking for granted that it is the optimal detection order), respectively. We iteratively perform the traditional algorithm to achieve high diversity degree for each substream. First, we perform the detection algorithm to get initial decisions $\hat{s}_4^0$, $\hat{s}_3^0$, $\hat{s}_2^0$ and $\hat{s}_1^0$ corresponding to substreams c_4, c_3, c_2, c_1, respectively. Then we begin the iteration. In the first loop, we subtract $\hat{s}_1^0$, which has the highest diversity degree 4, from the total receive signal, and then we decode the remaining (3, 4) system using the traditional algorithm. This completes the first loop, and we get the first updated decisions $\hat{s}_4^1$, $\hat{s}_3^1$, $\hat{s}_2^1$ and $\hat{s}_1^0$. In the second loop, we subtract both $\hat{s}_1^0$ and $\hat{s}_2^1$ from the total receive signal, then get the second decisions $\hat{s}_4^2$ and $\hat{s}_3^2$. In the last loop, we subtract $\hat{s}_1^0$, $\hat{s}_2^1$ and $\hat{s}_3^2$ from the total receive signal and get the third decision $\hat{s}_4^3$. Finally, decisions $\hat{s}_4^3$, $\hat{s}_3^2$, $\hat{s}_2^1$ and $\hat{s}_1^0$ are decoding results.

It may be helpful to understand the performance improvement by analysing the change of diversity degree of each substream in each loop of our algorithm, which is shown in Table 1.

Table 1: Change of diversity degree in each loop

Detection state	Detection order in each state	Diversity degree of c_4, c_3, c_2, c_1, respectively
Initialisation	$\hat{s}_4^0 \rightarrow \hat{s}_3^0 \rightarrow \hat{s}_2^0 \rightarrow \hat{s}_1^0$	1, 2, 3, 4
Loop 1	$\hat{s}_1^0 \rightarrow \hat{s}_4^1 \rightarrow \hat{s}_3^1 \rightarrow \hat{s}_2^1$	2, 3, 4, 4
Loop 2	$\hat{s}_1^0, \hat{s}_2^1 \rightarrow \hat{s}_4^2 \rightarrow \hat{s}_3^2$	3, 4, 4, 4
Loop 3	$\hat{s}_1^0, \hat{s}_2^1, \hat{s}_3^2 \rightarrow \hat{s}_4^3$	4, 4, 4, 4

In general, we give the following algorithm for an (m, n) MIMO system where $m \leq n$.

Initialisation:

1. Perform the optimal detection order operation put forward in [1]. After this we assume that the order $m, m-1, \ldots, 1$ is the optimal order.
2. Decode each substream of the (m, n) system by using traditional algorithm.

Recursion:

For $i = 1$ to $m - 1$ do:
3. Subtract signals $(\tilde{s}_1, \tilde{s}_2, \ldots, \tilde{s}_i)$ from substreams 1 to i as $\tilde{r} = r - \sum_{j=1}^{i} h_j \tilde{s}_j$.
4. Apply the traditional algorithm to the remaining $(m - i, n)$ system to generate $(\tilde{s}_{i+1}, \tilde{s}_{i+2}, \ldots, \tilde{s}_m)$.

Simulation results and conclusions: In this Section we demonstrate the performance improvement of our new algorithm via simulations. The results of the (4, 4) system are shown in Fig. 1. At the transmitter bits are modulated with 16QAM at each transmit antenna. The performance of the actual BER performance with error propagation is also plotted for comparison. As evident from the Figure, a large performance gain is achieved using our iterative algorithm. For example, at the BER of 0.1% our new algorithm with three loop times outperforms the traditional algorithm by about 3.7 dB.

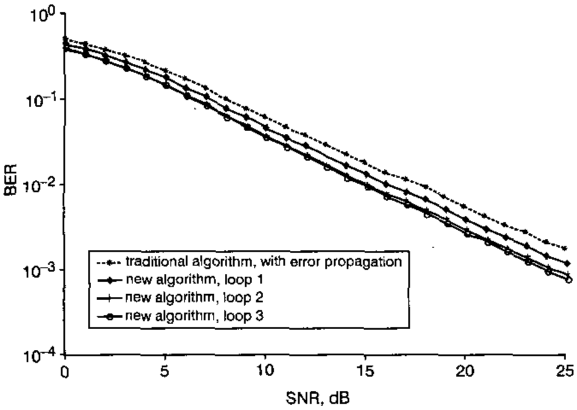

Fig. 1 *BER performance of new algorithm in each loop, (4, 4) system*

It is also worth noting that the better performance achieved in our algorithm is at the expense of a reasonable complexity, which makes our algorithm more practical for implementation. The complexity of our algorithm equals to that of the traditional algorithm multiplying the loop times. From our simulation results it is also clear that the performance gain between two conjoint loops degrades as the loop times increase. It is also clear from the simulation results that if we only loop two times, the performance gain offered by iteration has been mostly achieved. More than two loop times does little to the performance improvement, which makes it possible to reduce the complexity by decreasing the loop times, with relatively very little performance loss. This indicates that our algorithm is feasible to make a trade-off between performance and complexity.

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References

1 WOLNIANSKY, P.W., FOSCHINI, G.J., GOLDEN, G.D., and VALENZUELA, R.A.: 'V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel'. Proc. ISSSE'98, Pisa, Italy, 1998 pp. 295–300

2 BARO, S., BAUCH, G., PAVLIC, A., and SEMMLER, A.: 'Improving BLAST performance using space-time block codes and turbo decoding'. Proc. GLOBECOM'00, San Francisco, CA, USA, 2000, Vol. 2, pp. 1067–1071

3 CHOI, W.J., NEGI, R., and CIOFFI, J.M.: 'Combined ML and DFE decoding for the V-BLAST system'. Proc. ICC'00, New Orleans, LA, USA, 2000, Vol. 2, pp. 1243–1248

Influence of channel estimation error on layered space-time receivers

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The performance limitation due to the imperfect channel estimation in a layered space-time (BLAST) receiver is addressed. For the performance evaluation, the effective signal-to-interference ratio and average bit error rate expressions of zero forcing VBLAST systems with unordered successive cancellation are derived taking into account the effect of the imperfect channel information.

Introduction: A while ago, a layered space-time (BLAST) architecture was proposed to overcome the link budget, which transmits parallel data streams using multiple antennas [1, 2]. However, BLAST systems require accurate channel state information derived in a multiple input multiple output (MIMO) architecture, since the signal received at the receiver antennas is the superposition of the signals transmitted from multiple antennas and its performance is heavily dependent on the estimation error, which is introduced by the additive noise in the common pilot symbol [3, 4].

In this Letter we report investigation of the effects of the imperfect channel estimation in vertical BLAST (VBLAST) systems based on zero forcing (ZF) filtering. For the purpose of measuring performance, using Gaussian approximation on the error propagation, the effective signal-to-interference ratio (SIR) and average bit error rate (BER) expressions are derived in the presence of the imperfect channel information for two special cases of the best and worst symbol cancellations. Numerical results demonstrate the influence of the imperfect channel information on the BER performance of unordered ZF-VBLAST systems employing the least square (LS) and linear minimum mean square error (LMMSE) estimators for the channel estimation.

ZF-VBLAST system model: We use $M \times N$ to signify a configuration with M transmit and N receive antennas. Denoting the transmitted signal for mth parallel stream by x_m, the M-dimensional signal vector $\mathbf{x} = [x_1\ x_2\ \cdots\ x_M]^T$ has variance $\mathrm{E}\{\mathbf{x}\mathbf{x}^H\} = (S_p/M)\,\mathbf{I}_M$, where S_p is the total transmitted symbol power, which is held constant regardless of the number of transmit antennas, $(\cdot)^H$ denotes the Hermitian transpose, and $\mathbf{I}_M$ stands for an $M \times M$ identity matrix. Using the discrete-time complex baseband model, the channel impulse response has an $N \times M$ matrix denoted by $\mathbf{H}$, the elements of which form jth transmit antenna to ith receive antenna and are expressed as H_{ij} and are mutually uncorrelated complex Gaussian random variables (r.v.'s) with zero mean and unit variance in a rich scattering environment. The received symbol vector is then obtained as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} = \sum_{i=1}^{M} \mathbf{h}_i x_i + \mathbf{w} \tag{1}$$

where $\mathbf{h}_i$ is the ith column of $\mathbf{H}$ and $\mathbf{w}$ is an additive Gaussian noise with covariance $(N_0/2)\,\mathbf{I}_M$. The ZF-VBLAST is based on the QR decomposition of the estimated channel response matrix $\hat{\mathbf{H}} = \mathbf{H} + \varepsilon$, which is formulated as $\hat{\mathbf{H}} = \hat{\mathbf{Q}}\hat{\mathbf{R}}$, where $\hat{\mathbf{R}}$ is an upper triangular matrix and $\hat{\mathbf{Q}}$ is an orthogonal matrix satisfied with $\hat{\mathbf{Q}}^H\hat{\mathbf{Q}} = \mathbf{I}$.

Using the estimated nulling vector (or beamformer), the $M \times 1$ beamformer output vector can be expressed as

$$\mathbf{z} = \hat{\mathbf{Q}}^H\mathbf{y} = \hat{\mathbf{R}}\mathbf{x} - \underbrace{\hat{\mathbf{Q}}^H\varepsilon\mathbf{x}}_{\mathbf{E}} + \underbrace{\hat{\mathbf{Q}}^H\mathbf{w}}_{\hat{\mathbf{w}}} \tag{2}$$

where ε is an $N \times M$ channel estimation error matrix the elements of which ε_{ij} are assumed to be a Gaussian r.v. with variance σ_ε^2 and $\hat{\mathbf{w}}$ is an $M \times 1$ AWGN vector with covariance matrix $N_0/2\ \mathbf{I}_M$.

In ZF-VBLAST systems with unordered interference cancellation, the detection is performed by the descending order of the transmitted stream, [1, 2]. In each step, a nulling vector for the kth stream is updated by using the estimated channel matrix $\hat{\mathbf{H}}$. So, in kth turn, the decision variable of $(M-k+1)$th stream can be decomposed into the following signal components:

$$\begin{aligned} z_{M-k+1} = {} & \hat{r}_{M-k+1,M-k+1}x_{M-k+1} + I_{M-k+1} \\ & - E_{M-k+1} + \hat{w}_{M-k+1} \end{aligned} \tag{3}$$

where $I_i = \sum_{l=i+1}^{M} \hat{r}_{i,l}\,(x_l - \hat{x}_l)$ is the interference signal in the ith stream due to the imperfect symbol cancellation, E_i is the interference term due to the channel estimation error, and $\hat{w}_i$ is the AWGN term in the ith stream. The symbol decision is based on the quantisation function as $\hat{x}_l = Q(z_l/\hat{r}_{l,l})$.

BER expression in presence of estimation error: Recall that the second term in (3) is the interference term due to imperfect decision feedbacks. To quantify the effect of interference, we may approximate it as a Gaussian random variable. The interfering term I_i is dependent on the symbol error in the previously detected streams and the