Efficient Detection of Space-Time Block Codes Based on Parallel Detection

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ABSTRACT

Algorithms based on the QR decomposition of the equivalent space-time channel matrix have been proved useful in the detection of V-BLAST systems. Especially, the parallel detection (PD) algorithm offers ML approaching performance up to 4 transmit antennas with reasonable complexity. We show that when directly applied to STBCs, the PD algorithm may suffer a rather significant SNR degradation over ML detection, especially at high SNRs. However, simply extending the PD algorithm to allow $p \geq 2$ candidate layers, i.e. p-PD, regains almost all the loss but only at a significant increase in complexity. Here, we propose a simplification to the p-PD algorithm specific to STBCs without a corresponding sacrifice in performance. The proposed algorithm results in significant complexity reductions for moderate to high order modulations.

Key Words : Detection complexity, multiple transmit antennas, parallel detection (PD), QR-decomposition, space-time block codes(STBCs)

Ⅰ. Introduction

It is well known that multiple-input multiple-output (MIMO) techniques using multiple transmit and receive antennas dramatically improve the capacity of wireless communication systems under rich multipath fading channels[1-2]. Practical multiple antenna transmission schemes are generally classified into spatial multiplexing and/or space-time coding[3].

Spatial multiplexing such as the Vertical Bell Labs Layered Space-Time (V-BLAST) scheme is a transmission scheme where independent data signals are simultaneously transmitted over distinct transmit antennas. In V-BLAST systems, detection algorithms based on the QR decomposition of the equivalent space-time channel matrix have been proved useful[4-6] and algorithms, such as decision feedback (DF)[4], combined maximum likelihood (ML) and DF[5], parallel detection (PD)[6] and p-PD[7-8] have been developed.

The PD algorithm[6] is an improvement on the DF algorithm where a layer called the candidate layer is chosen and DF algorithm is applied to the remaining layers for each of the candidate symbols in the candidate layer. The final decision is made by minimizing the Euclidean distance between the received vector and the candidate vectors generated. The p-PD algorithm[7-8] is a direct extension of the PD algorithm where $p \geq 2$ candidate layers are allowed. At least up to 4 transmit antennas, the PD algorithm offers ML approaching performance with reasonable complexity. However, performance significantly degrades with increasing number of antennas[7]. For number of transmit antennas exceeding 4, the number of candidate layers must be increased beyond 1 in order to maintain ML approaching performance. However, using more than one candidate layer results in significant increase in

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detector complexity[7].

Space-time coding, on the other hand, is a coding technique appropriate for multiple transmit antennas with the main objective of obtaining spatial diversity[9-10]. In this paper, we focus on decoding of STBCs[11-15]. Without additional structure, the ML detection complexity for general STBCs using Q-ary QAM modulation with N transmit and M receive antennas is proportional to MQ^N which quickly becomes impractical as N and/or Q increases.

Recently, an attempt was made to apply the DF algorithm to the detection of STBCs which resulted in severe performance losses over ML detection[15]. In order to achieve ML approaching performance with reasonable complexity, sphere decoding techniques were applied to the detection of STBCs in[16-18]. Clearly, other promising V-BLAST detection algorithms, such as PD and p-PD algorithms may be applied to space-time block coded systems possessing equivalent space-time channel matrices[15] with appropriate modifications.

In this paper, we first apply the PD and p-PD algorithms to STBCs[1)]. For STBCs considered in this paper, the PD algorithm is approximately 1~2 dB inferior to ML detection at an average symbol error rate (SER) of 10^{-3}, depending on the modulation order and the code employed. However, the p-PD algorithm with $p=2$ regains almost all the loss at the cost of significant increase in complexity. We then propose simplifications to the PD and the p-PD algorithms specific to STBCs without noticeable sacrifices in performance. The proposed algorithms result in significant complexity reductions for moderate to high order modulations.

The remainder of this paper is organized as follows. In Section II, we present the system and channel models and in Section III, the proposed detection algorithms are derived. In Section III, simulation results are presented and conclusions are drawn in Section V.

1) The PD and p-PD algorithms can be applied to general STBCs which can be represented using the equivalent space-time signal model[15].

Ⅱ. System and Channel Model

We consider full-rate and delay-optimal[10][2)] STBCs for systems with N transmit antennas. Though, for presentation purposes, we only consider the case of one receive antenna, the results can easily be extended to the case of multiple receive antennas. Let us denote the transpose of a matrix $\boldsymbol{A}$ by $\boldsymbol{A}^T$. At the transmitter, N, Q-ary QAM modulated symbols are grouped into a column vector of length N, denoted $\boldsymbol{x}^T=[x_1,\cdots,x_N]$ which is then input to a space-time encoder to form a codeword matrix $\boldsymbol{G}(\boldsymbol{x})=\{g_{t,n}\}$ of size $N\times N$. The symbol $g_{t,n}$ is then transmitted on the nth transmit antenna at the tth time interval. The signals transmitted on different transmit antennas are assumed to experience independent Rayleigh fading. The channel is also assumed to be quasi-static in the sense that the channel response does not vary significantly during the transmission of a codeword matrix. The matched filter output at the receive antenna on the tth time interval, denoted y_t, is then given by

$$y_t=\frac{1}{\sqrt{N}}\sum_{n=1}^{N}h_n g_{t,n}+w_{t,}\ t=1,2,\cdots,N. \qquad (1)$$

Here, w_t represent the contribution of the AWGN with a two-sided power spectral density of $N_0/2$ and are zero mean independent and identically distributed (i.i.d.) spherically symmetric complex Gaussian random variables with variance $N_0/2$ per dimension. The channel coefficients h_n represent the complex channel gain between the nth transmit and the receive antennas and are zero mean i.i.d. spherically symmetric complex Gaussian random variables with variance $1/2$ per dimension. Finally, the transmit power at the transmit antennas is normalized so that the total average transmit power

2) STBCs are referred to as being full-rate if $T=L$ where T is the number of time slots used to transmit a codeword matrix and L is the number of information symbols transmitted per codeword matrix. If, in addition, $T=N$, the STBCs are referred to as being delay-optimal.

is equal to that of a single transmit antenna system. The received vector denoted $y^T=[y_1,\cdots,y_N]$, can then be written as

$$Y=\frac{1}{\sqrt{N}}GH+w \quad (2)$$

where $h^T=[h_1,\cdots,h_N]$ and $w^T=[w_1,\cdots,w_N]$. We assume that the received vector can be rearranged into the following equivalent space-time signal model[15]:

$$\hat{y}=Hx+\hat{w} \quad (3)$$

where $\hat{y}$ is obtained by complex conjugating appropriate elements of y. The matrix H is the equivalent space-time channel matrix of size $N\times N$ assumed to be of full rank, composed of a complex linear combination of $h_1,\cdots,h_N$ and their complex conjugates[3)]. Also, $\hat{w}$ represents the modified noise vector of size $N\times 1$ composed of $w_1,\cdots,w_N$ and their complex conjugates.

Performing the QR decomposition of the equivalent space-time channel matrix H, we have $H=QR$ where Q is a unitary matrix of size $N\times N$ and $R=\{R_{i,j}\}$ is an upper triangular matrix of size $N\times N$. Left multiplying $\hat{y}$ by Q^H, we obtain

$$\tilde{y}=Q^H\hat{y}=Rx+\tilde{w} \quad (4)$$

where $\tilde{w}=Q^H\hat{w}$ possesses the same statistical properties as w. This form allows us to apply various existing V-BLAST detection algorithms to the detection of STBCs. In Figs. 3-4, we observe the average SER curves of ML, DF, PD and 2-PD algorithms applied to the A-ST-CR[12-13] and the ST-CR codes[11] for $Q=4,16,64,256$ with $N=4$ and $M=1$, respectively. Column ordering within H for the PD and 2-PD algorithms, i.e. the selection of candidate layers, was not optimized since the effect of column ordering was insignificant. Observe that the PD algorithm is approximately 1~2 dB inferior to ML detection at an SER of 10^{-3}, depending on the modulation order and the code employed. However, the 2-PD algorithm offers performance virtually identical to that of the ML detection for both codes. Though the detector complexity of PD and p-PD algorithms are significantly smaller than that of ML detection, they may still be prohibitively large for large modulation orders.

3) Note that most well-known STBCs such as orthogonal-STBCs[10], quasi-orthogonal STBCs[19], space-time constellation-rotating (ST-CR) codes[11], Alamouti-ST-CR (A-ST-CR) codes[12-13] and codes for IEEE 802.16e systems[20] can be represented using the above equivalent space-time signal model.

Ⅲ. Proposed Algorithms

The PD algorithm first chooses an initial candidate layer and the DF algorithm is applied to the remaining layers for each of the candidate symbols in the candidate layer which results in Q distinct candidate vectors of length N. Other than the QR decomposition itself, the computational load of minimizing the Euclidean distance between the resulting Q candidate vectors and $\tilde{y}$ dominates the overall complexity of the algorithm, especially for large value of Q. The key observation in reducing the number of resulting candidate vectors without a significant loss in performance is that the candidate symbols generated for a given layer may not all be distinct.

The first proposed algorithm, referred to as the *recursive reordered PD* (RR-PD) algorithm, first chooses an initial candidate layer at random and the DF algorithm is applied to the first J remaining layers $(1\le J\le N-1)$ for each of the Q candidate symbols in the candidate layer. Fig. 1 shows the flowchart of the proposed RR-PD algorithm. Let $\tilde{x}_{N-i+1}(q)$, $q=1,\cdots,Q$, denote the candidates of $x_{N-i+1}(q)$ in the ith layer. In Fig. 1, $D(\cdot)$ indicates the hard decision operation. Also, let us denote the resulting number of distinct candidates in the ith layer as α_i, $1\le\alpha_i\le Q$, $i=1,\cdots,J+1$, where $i=1$ corresponds to the bottommost layer. We then perform a simple column ordering within H so that the layer with the minimum number of

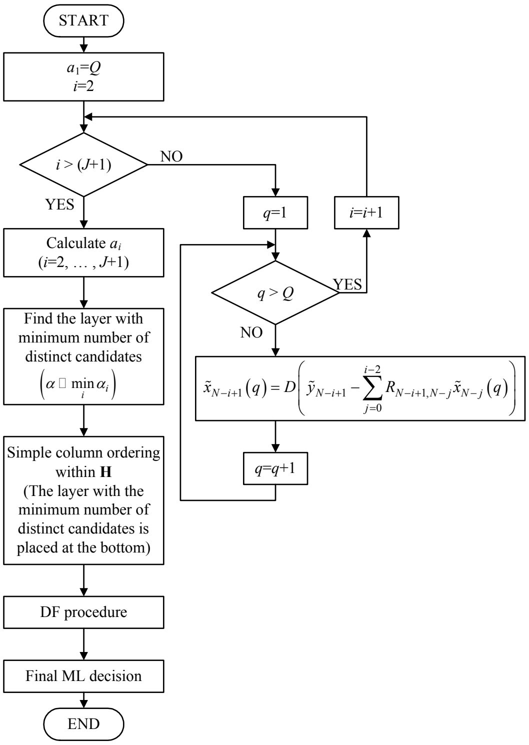

Fig. 1. Flowchart of the proposed RR-PD algorithm.

distinct candidates after the PD procedure is placed at the bottom, thus replacing the original candidate layer. After this ordering, the DF procedure is once again applied to all the remaining layers for each of the $\alpha = \min_i \alpha_i \leq Q$ candidate symbols in the candidate layer. Note that we do not consider ordering within the remaining layers. Also, note that the algorithm guarantees that the number of distinct candidate symbols in the candidate layer and thus, the number of resulting distinct candidate vectors, α, is always less than or equal to Q. Therefore, the search space for the final ML decision operation is also reduced from Q to α. Compared to the PD algorithm, the RR-PD algorithm requires an additional QR decomposition procedure after the column reordering. Hence, the algorithm is useful only if α is significantly smaller than Q, on the average, in order to justify the additional QR decomposition procedure. In Section IV, we show that the average number of resulting distinct candidate vectors is indeed small enough for $Q \geq 64$ and significant complexity reductions are obtained.

The second algorithm, referred to as the *recursive reordered p-PD* (RR-p-PD) algorithm, is a direct extension of the RR-PD algorithm based on the p-PD algorithm[7-8]. The RR-p-PD algorithm first chooses $p \geq 2$ layers at random as initial candidate layers and the DF algorithm is applied to the first K remaining layers, $p \leq K \leq N-p$, for each of the p-tuple candidate symbol vectors. Fig. 2 shows the flowchart of the proposed RR-p-PD algorithm. Let $\tilde{\boldsymbol{x}}_p = [\tilde{x}_{N-p+1}(n), \cdots, \tilde{x}_N(n)]$, $n = 1, \cdots, Q^p$, denote all possible distinct p-tuple candidate vectors of the symbol vector $\boldsymbol{x}_p = [x_{N-p+1}(n), \cdots, x_N(n)]$ in the initial candidate layers where each element of $\boldsymbol{x}_p$ is one of the Q candidate symbols. Again, the expectation is that the minimum number of distinct candidate symbols in the K non-candidate layers is sufficiently smaller than Q^p. After the initial DF procedure, we perform a column ordering within $\boldsymbol{H}$ so that p layers with the minimum number of

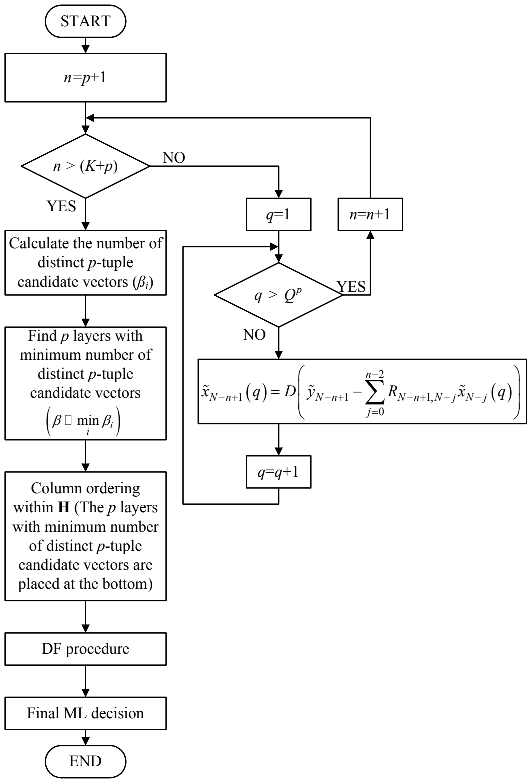

Fig. 2. Flowchart of the proposed RR-p-PD algorithm.

distinct p-tuple candidate vectors are placed at the bottom, thus replacing the original candidate layers. Denote by β_i, $i=1,\cdots,\binom{K}{p}$, the number of distinct p-tuple candidate vectors in all possible $\binom{K}{p}$ combinations of p layers selected from the K non-candidate layers after the initial PD procedure and let $\beta=\min_i \beta_i$. The p-tuple combination corresponding to β are then selected as the new candidate layers after which the DF procedure is applied to each of the β, p-tuple candidate symbol vectors. This procedure reduces the search space of the final ML decision operation from Q^p to β. Again, β should be sufficiently smaller than Q^p, on the average, and we find that this is true for $Q \geq 16$ for the STBCs considered. Table I lists the decoding complexities in terms of the required number of real multiplications and additions for the proposed RR-PD and RR-p-PD algorithms.

Table 1. Decoding complexities for proposed algorithms.

	Number of real multiplications	Number of real additions
RR-PD $(J=1)$	$4Q+2\alpha(N^2+N)$ $+2(4N^3-N^2)$	$4Q+2(4N^3-3N^2)$ $+\alpha(2N^2+2N-1)$
RR-p-PD $(p=2, K=2)$	$20Q+2(4N^3-N^2)$ $2\beta(N^2+N-2)$	$14Q+6Q^2$ $+2(4N^3-3N^2)$ $+\beta(2N^2+2N-5)$

Ⅳ. Simulation Results

In this section, we present the average SER performance along with the required computational complexity for the proposed algorithms for the case when $N=4$ and $M=1$ for the A-ST-CR[12-13] and the ST-CR[11] codes. Figs. 3-4 show the average SER curves of the A-ST-CR and the ST-CR codes versus E_b/N_0 for various detection strategies where E_b is the average received energy per information bit. Note that RR-PD with $J=1$ and RR-p-PD with $p=2$ and $K=2$ show performance virtually identical to that of the PD and ML/p-PD detection, respectively.

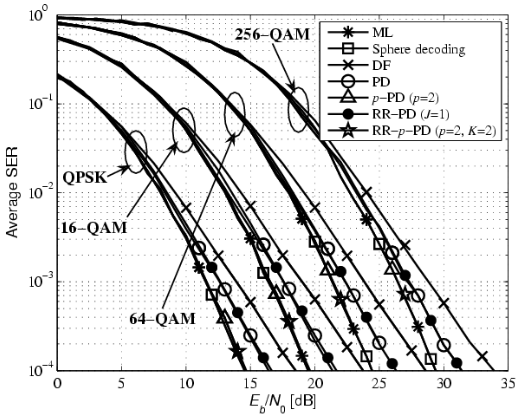

Fig. 3. Average SER curves of the conventional and proposed algorithms for the A-ST-CR code[12-13] versus E_b/N_0 for QPSK, 16-QAM, 64-QAM and 256-QAM with $N=4$ and $M=1$ under Rayleigh fading channel.

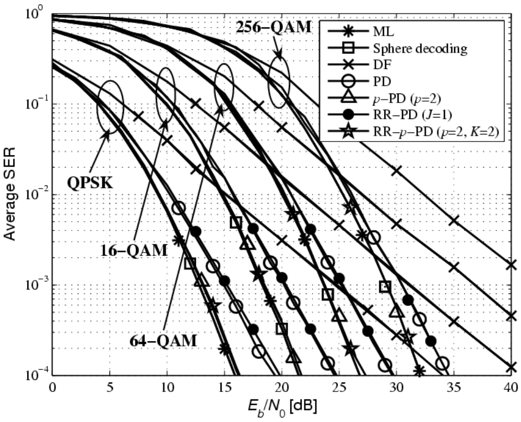

Fig. 4. Average SER curves of the conventional and proposed algorithms for the ST-CR code[11] versus E_b/N_0 for QPSK, 16-QAM, 64-QAM and 256-QAM with $N=4$ and $M=1$ under Rayleigh fading channel.

In Table II, we list the average values of α and β for the A-ST-CR and the ST-CR codes with $N=4$ and $M=1$. Note that the average values of α for PD reduce monotonically to very small values with increasing J. As a result of the trade-off between the increase in complexity due to the repeated application of the DF algorithm for the J layers and the reduction in complexity due to the reduced number of distinct candidate vectors, an optimum value of J exists minimizing the overall complexity. For both the A-ST-CR and the ST-CR codes, the optimum value of J was found to be

Table 2. Average values of α and β of the A-ST-CR and ST-CR codes with $N=4$ and $M=1$ at an SER=10^{-3} under Rayleigh fading channel.

Code	Modulation	Average values of α			Average values of β
		$J=1$	$J=2$	$J=3$	$K=2$
A-ST-CR	QPSK	1.18	1.03	1.02	1.83
	16-QAM	2.70	1.23	1.22	11.43
	64-QAM	7.56	1.70	1.68	105.9
	256-QAM	24.15	2.64	2.63	1199.53
ST-CR	QPSK	1.54	1.27	1.18	3.51
	16-QAM	4.35	3.09	2.73	26.7
	64-QAM	14.11	9.21	7.93	252.04
	256-QAM	50.36	30.81	25.98	2873.81

$J=1$. Note that the average values of β for 2-PD also reduce to very small values compared to the number of the initial candidate vectors, Q^2. Furthermore, we found the average values of α and β to be significantly insensitive to changes in SNR, rendering the overall complexity to be insensitive to changes in SNR.

Tables III-IV list the detection complexities for the conventional and proposed algorithms for the A-ST-CR and the ST-CR codes, as measured in terms of the required number of real multiplications and additions. The RR-PD and RR-2-PD algorithms result in significant complexity reductions for moderate to high order modulations compared to PD and 2-PD. For QPSK, the detection complexities of the RR-PD and RR-2-PD algorithms are comparable to those of the PD and 2-PD algorithms. However, for $Q=16,64,256$, we observe complexity reduction factors in the range of 0.18 to 0.76 with RR-PD compared to PD in terms of the required number of real multiplications. Also, complexity reduction factors in the range of 0.62 to 0.95 are achievable with RR-2-PD compared to 2-PD in terms of the required number of real multiplications for $Q=16,64,256$. Complexity reduction factors with RR-PD and RR-2-PD in terms of required number of real additions are similar to those in terms of the required number of real multiplications. Note that complexity reductions for the RR-PD and the RR-2-PD algorithms become more prominent with increasing modulation orders where the

Table 3. Comparison of decoding complexities in terms of the required number of (real) multiplications for conventional and proposed algorithms for the A-ST-CR and ST-CR codes with $N=4$ and $M=1$ at an SER=10^{-3} under Rayleigh fading channel.

Code	Algorithm \ Modulation	Number of real multiplications			
		QPSK	16-QAM	64-QAM	256-QAM
A-ST-CR	ML	18432	4.7×10^6	1.2×10^9	3.1×10^{11}
	Sphere decoding	468	1325	9631	138645
	PD	400	880	2800	10480
	RR-PD ($J=1$)	544	652	1039	2470
	p-PD ($p=2$)	576	4656	67056	1053936
	RR-p-PD ($p=2, K=2$)	626	1212	5573	48784
ST-CR	ML	18432	4.7×10^6	1.2×10^9	3.1×10^{11}
	Sphere decoding	484	1377	11259	220265
	PD	400	880	2800	10480
	RR-PD ($J=1$)	558	718	1301	3519
	p-PD ($p=2$)	576	4656	67056	1053936
	RR-p-PD ($p=2, K=2$)	687	1762	10834	109058

Table 4. Comparison of decoding complexities in terms of the required number of (real) additions for conventional and proposed algorithms for the A-ST-CR and ST-CR codes with $N=4$ and $M=1$ at an SER=10^{-3} under Rayleigh fading channel.

Code	Algorithm \ Modulation	Number of real additions			
		QPSK	16-QAM	64-QAM	256-QAM
A-ST-CR	ML	18176	4.6×10^6	1.1×10^9	3.0×10^{11}
	Sphere decoding	422	1960	20507	305563
	PD	364	832	2704	10192
	RR-PD ($J=1$)	479	586	967	2382
	p-PD ($p=2$)	840	9648	148560	2363088
	RR-p-PD ($p=2, K=2$)	633	2577	29595	439200
ST-CR	ML	18176	4.6×10^6	1.1×10^9	3.0×10^{11}
	Sphere decoding	483	2201	26088	499035
	PD	364	832	2704	10192
	RR-PD ($J=1$)	493	650	1223	3405
	p-PD ($p=2$)	840	9648	148560	2363088
	RR-p-PD ($p=2, K=2$)	691	3111	34710	497800

implementation complexity of other algorithms start becoming problematic.

The detection complexities of the RR-2-PD algorithm are approximately 35%~96% of those of the sphere decoder in terms of the required number of real multiplications for $Q=64,256$. However, the detection complexities of the RR-2-PD algorithm are approximately 31%~44% larger than those of the sphere decoder in terms of the required number of real additions for $Q=64,256$ except for the ST-CR code with $Q=256$. Nevertheless, the complexity reduction in the required number of real multiplications is significant larger than the complexity increase in the required number of real additions.

Ⅴ. Conclusions

In this paper, efficient detection algorithms of STBCs based on QR decomposition of the equivalent space-time channel matrix were proposed. The proposed algorithms are general and apply to general STBCs which can be represented using the equivalent space-time signal model. The proposed RR-PD and RR-p-PD algorithms show performance virtually identical to that of PD and ML/p-PD detection. The proposed algorithms result in significant complexity reductions for moderate to high order modulations.

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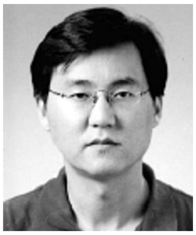

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