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Improved QR Decomposition-Based SIC Detection Algorithm for MIMO System

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Abstract: Multiple-Input Multiple-Output (MIMO) systems can increase wireless communication system capacity enormously. Maximum Likelihood (ML) detection algorithm is the optimum detection algorithm which computational complexity growing exponentially with the number of transmit-antennas, which makes it difficult to use it in practice system. Ordered Successive Interference Cancellation (SIC) algorithm with lower computing complexity will suffer from error propagation when an incorrect symbol is selected in the early layers. An MIMO signal detection algorithm based on Improved Sorted-QR decomposition (ISQR) is presented in this study. According to the rule of SNR, ISQR can obtain the optimum detection order with less calculation. Based on ISQR an improved detection algorithm is proposed which providing 2 adjustable parameters. Trade-off between performance and complexity can be selected properly by setting the 2 parameters at different values. Simulation experiments are given under the multiple scattering wireless communication environments and the simulation experiment results show the validity of proposed algorithm.

Keywords: Maximum likelihood detection, MIMO, QR-decomposition, successive interference cancellation

INTRODUCTION

Spatial Multiplexing Multiple-Input Multiple-Output (MIMO) systems with rich scattering wireless channels can provide enormous capacity improvements without increasing the bandwidth or transmitted power. Channel capacity linearly increases with the number of antennas. In MIMO system, a serial data stream is converted to parallel, with each data symbol transmitted on a separate antenna. In order to decode symbols corrupted by inter-antenna interference, efficient signal detection algorithms for MIMO systems have attracted much interest in recent years. Many detection techniques had been proposed such as zero forcing linear detection, minimum mean-square error linear detector, Maximum Likelihood (ML) detection, Bell-Labs layered space-time detection, etc.

Among these schemes, ML detection is the optimized detection algorithm when considering the performance of Bit-Error Rate (BER), but the computational complexity of ML detection increases exponentially with the number of transmit-antennas and the order of modulation which makes it difficult to use ML detection in practical system. Linear detection algorithms have low computation complexity comparing with ML detection, but the performance is also lower than that of ML detection. A lot of efforts have been put into the search of detection algorithms achieving ML or near-ML performance with lower complexity. The popular reduced-complexity alternative technique is the V-BLAST detection algorithm and QR decomposition-based successive interference cancellation detection algorithm. For these detection algorithms, incorrect symbol detection in the early layers will create errors in the following layers, so they are easy to suffer from the error propagation problem. The following layers depend highly on the results of the first detected layers (Foschini and Gans, 1998; Telatar, 1999; Zheng *et al*., 2011; Seethaler and Bolcskei, 2010; Zhang *et al*., 2012; Chen and Sheen, 2011; Chen and Yu, 2007; Chen *et al*., 2007; Xu *et al*., 2008).

In order to improve the detection performance, the first detected layers should be cancelled perfectly. Some improved detection algorithms have been proposed in the literatures. Two kinds of detection method are combined together, or different searching methods like tree search are used in MIMO detection. Ordered QR decomposition of channel matrix can be utilized to reduce the complexity of detection at the cost of lowing performance. Inspired by this idea, we introduce a new sorted method which can obtain the best detection order according to the rule of SNR without calculations of pseudo-inverses (Wolniansky *et al*., 1998; Golden and Foschini, 1999; Chang *et al*., 2010; Kyeong *et al*., 2008).

On the other hand, due to the error propagation, the overall performance is determined by the first layers to be decoded, we proposed an improved method to increase the validity of the first layers detection (Lin

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and Wu, 2011; Myung-Sun *et al*., 2009; Chang and Chung, 2012; Goldberger and Leshem, 2011; Studer and Bolcskei, 2010). After performing improved sorted QR decomposition of the channel matrix, the ML detection of symbols with length L is performed and the partial accumulated metrics are calculated and ordered, which gives a sequence set of the first L layers, from the sequence, we select the first T sequences from the set with the smallest partial accumulated metrics, then successive interference cancellation algorithm is used to search the left layers (Jia *et al*., 2008; Kang *et al*., 2008; Wübben *et al*., 2001). Finally, the minimum accumulated metric symbol is put out as the transmitted symbols. The proposed scheme provides 2 trade-off parameters with better performance and low complexity.

SYSTEM MODEL AND ORIGINAL ALGORITHM

Description of system model: Here we consider the un-coded MIMO system consisting of M transmitted antennas at the transmitter and N antennas at the receiver (M≤N). The wireless channel is assumed to be quasi-static, so that the channel remains constant during a block of certain length and changes to an independent realization for the next block. The received signal vector can be represented as:

$$\boldsymbol{y}(t) = \boldsymbol{H}(t)\boldsymbol{x}(t) + \boldsymbol{n}(t) \tag{1}$$

where,

$\boldsymbol{x}(t) = \left[x_1(t),...,x_M(t)\right]^{\mathrm{H}}$: The sent symbols

$\boldsymbol{y}(t) = \left[y_1(t),...,y_N(t)\right]^{\mathrm{H}}$: The received symbols

$\boldsymbol{n}(t) = \left[n_1(t),...,n_N(t)\right]^{\mathrm{H}}$: The noise symbols

$(.)^{\mathrm{H}}$: Vector complex conjugate transposition

the symbols $x_m(t)$ and the noise $n_n(t)$ are mutually uncorrelated, zero-mean random processes with variances $E\{|x_m(t)|^2\} = 1$ and $E\{|n_n(t)^2|\} = \sigma^2$. The element h_{ij} of H(t) represents channel gains between the j^{th} transmitter and the i^{t} receiver antennas at the discrete time t. As the channel has slowly time varying flat fading and the channel state information H is known perfectly in the receiver, for brevity of notation the discrete time index t is abandoned in the subsequent consideration so the received signal vector can be described as:

$$\boldsymbol{y} = \boldsymbol{Hx} + \boldsymbol{n} \tag{2}$$

Maximum likelihood detection algorithm: For detecting transmitted symbols from the received signals, Maximum Likelihood (ML) detection of the transmitted signal can be formulated as finding:

$$\hat{\boldsymbol{x}} = \arg\min_{x}\{\|\boldsymbol{y} - \boldsymbol{Hx}\|^2\} \tag{3}$$

ML detection is an exhaustive searching which performs searching over the whole alphabet that the computational complexity is very high. It's very difficult to put ML detection into a practical system.

QR decomposition based Sucssicive Interference Cancellation (QR-SIC): With perfect state information of channel H, the ordered QR-decomposition of channel matrix is obtained firstly, H = QR, here Q is a N×M unitary matrix, $Q^{H}Q = I$, R is M×M upper triangular matrix. After left-multiplying received signal by:

$$\boldsymbol{Q}^{\mathrm{H}},\ \bar{\boldsymbol{y}} = \boldsymbol{Rx} + \bar{\boldsymbol{n}} \tag{4}$$

where, $\bar{\boldsymbol{y}}$ and $\bar{\boldsymbol{n}}$ are $M \times 1$ and $\bar{\boldsymbol{n}}$ have the equal statistical properties.

So the ML detection problem can be reformulated as:

$$\begin{aligned}\hat{\boldsymbol{x}} &= \arg\min_{\boldsymbol{x}}(\|\bar{\boldsymbol{y}} - \boldsymbol{Rx}\|^2) \\ &= \arg\min_{\boldsymbol{x}}\left(\sum_{i=1}^{M}\left|\bar{y}_i - \sum_{j=i}^{M}\boldsymbol{R}_{i,j}\hat{x}_j\right|^2\right)\end{aligned} \tag{5}$$

where,

$R_{i,j}$: The $(i, j)^{th}$ component of $\boldsymbol{R}$

$|\cdot|$: The absolute value

The vector $\hat{\boldsymbol{x}}$ depends on the constellation size of modulated signal and the number of transmit antennas.

V-BLAST: The classical V-BLAST detection algorithm is proposed by researchers of BELL Labs. It can be summarized as 4 steps: nulling, slicing, canceling and recurrence:

$$i \leftarrow 1; \boldsymbol{G}_1 = \boldsymbol{H}^+; k_1 = \arg\min_{j}\|(\boldsymbol{G}_1)_j\|^2; \tag{6}$$

$$\boldsymbol{w}_{k_i} = (\boldsymbol{G}_i)_{k_i}; \tilde{x}_{k_i} = \boldsymbol{w}_{k_i}{}^{\mathrm{T}}\boldsymbol{y}_i; \hat{x}_{k_i} = Q(\tilde{x}_{k_i}); \tag{7}$$

$$\boldsymbol{y}_{i+1} = \boldsymbol{y}_i - \hat{x}_{k_i}(\boldsymbol{H})_{k_i}; \tag{8}$$

$$\boldsymbol{G}_{i+1} = \boldsymbol{H}^{+}_{\bar{k}_i}; k_{i+1} = \arg\min_{j\notin(k_1,...k_i)}\|(\boldsymbol{G}_{i+1})_j\|^2; i \leftarrow i+1 \tag{9}$$

where,

$(G_i)_j$ = The k^{th}_i row of G_i

$\boldsymbol{H}_{\bar{k}_i}$ = The channel matrix with the column k_i^{th} has been zeroed

H^+ = $(H^H \ H)^{-1} \ H^H$ denotes the Moore-Penrose pseudo-inverse

w_{ki} = The weight vector which is chosen depending on the criterion of ZF or MMSE

In this detection algorithm, at each time instant, instead of jointly decoding the signals from all the transmit antennas, V-BLAST decodes the "strongest" signal firstly, then cancels the effect of this strongest transmit signal from each of the received signals and then proceeds to decode the "strongest" of the remaining transmit signal and so on. It is the optimum detection order, but there needs to calculate pseudo-inverse in each iteration, so the calculating complexity is much higher than that of QR-SIC.

Proposed algorithm:

Improved Sorted QR decomposition (ISQR): The detection order in V-BLAST becomes important to all the overall performance of the system. The optimal detection order is from the strongest to the weakest signal since it can minimize the error propagation from one step of detection to the next.

Estimated covariance matrix is written as follows:

$$\begin{aligned} \boldsymbol{\Phi}_{\boldsymbol{x}\boldsymbol{x}}^{\text{QR-SIC}} &= E((\boldsymbol{x}-\hat{\boldsymbol{x}})(\boldsymbol{x}-\hat{\boldsymbol{x}})^{H}) \\ &= E((\boldsymbol{x}-\boldsymbol{R}^{-1}\boldsymbol{Q}^{H}\boldsymbol{y})(\boldsymbol{x}-\boldsymbol{R}^{-1}\boldsymbol{Q}^{H}\boldsymbol{y})^{H}) \\ &= \sigma^2(\boldsymbol{R}^{-1}(\boldsymbol{R}^{-1})^{H}) \end{aligned} \quad (10)$$

The SNR of i^{th} layer can be described:

$$\text{SNR}_i = \frac{E[|x_i|^2]}{E\{\bar{n}_i\}^2[\boldsymbol{R}^{-1}(\boldsymbol{R}^{-1})^{H}]_{i,i}} = \frac{1}{\sigma^2\left\|(\boldsymbol{R})^{-1}_{i:}\right\|_2} \quad (11)$$

where,

$[.]_{i,i}$ = The i^{th} diagonal component of matrix $[.]$

$\left\|(R)^{-1}_{i:}\right\|_2$ = The 2-norm of the i^{th} row of $\boldsymbol{R}^{-1}$

From here, we notice that optimized ordered rule of SNR is equivalent to the order of row 2-norm of R.

In decomposition of the channel matrix, the layer of minimal $\|(R)_i\|_2$ should be put first and order of $\|(R)_i:\|_2$ should be sorted from minimum to maximum. Therefore, the order rule can satisfies the lowest layer of maximum SNR.

So after performing QR decomposition of H, the column order of R is rearranged by the sort of 2-norm of R. The permutation matrix is named P. Then the QR decomposition is performed with the re-arranged $\bar{\boldsymbol{R}}$. Now, the optimum detection ordered can be obtained through first QR decomposition, re-sorted and second QR decomposition and without calculating pseudo-inverses of the channel matrix H. The propose algorithm (named as ISQR) can use the modified Gram-Schmidt method, householder transformation and Givens transformation to further reduce calculating complexity.

Improved scheme to decrease the error of the first detection layers: Due to interference nulling and error propagation, the performance of V-BLAST is far from that of optimal ML detection scheme. We propose an improved algorithm combined the ML detection and SIC by setting 2 adjustable parameters and the trade-off between performance and complexity can be adjusted by setting the 2 parameters at different values.

In order to improve the detection performance of the first detected layers, referencing the idea of ML detection, we set the first parameter L and L layers (these layer's numbers are M, M-1,… L+1, respectively) are performed exhaustive search in the step after improved sorted QR decomposition. Then calculating the partial accumulated metrics as:

$$d(\lambda) = \sum_{i=M-L+1}^{M}\left|\bar{y}_i - \sum_{j=i}^{M}\boldsymbol{R}_{i,j}\hat{x}_j\right|^2 \quad (12)$$

where,

$\lambda = 1, \cdots |\Omega|^L$

Ω = The set of modulation constellation

$|\Omega|$ = The number of constellation points

Now we get $|\Omega|^L$ available candidate paths. Here we need to sort these sequences with the partial accumulated metrics. Without loss of generality that the symbol with lower index has smaller metrics in: $d(1) \le d(2) \le \ldots \le d(\lambda)$.

After these preparations, we set another parameter T, then T candidate signal sequences with smaller partial accumulated metrics $d(1) \le d(2) \le \ldots \le d(T)$) are selected and the searching for left layers from M-L, M-L-1,…, 1 can be performed by SIC algorithm according to the ordered set mentioned above.

Then we get L candidate signal sequences with length M. The accumulated metrics are calculating for all the L candidates as:

$$\hat{\boldsymbol{x}} = \arg\min_{\boldsymbol{x}}\left(\sum_{i=1}^{M}\left|\bar{y}_i - \sum_{j=i}^{M}\boldsymbol{R}_{i,j}\hat{x}_j\right|^2\right) \quad (13)$$

At last, the candidate signal sequence with the smallest accumulated metrics is quantization and decision as the transmitted signal.

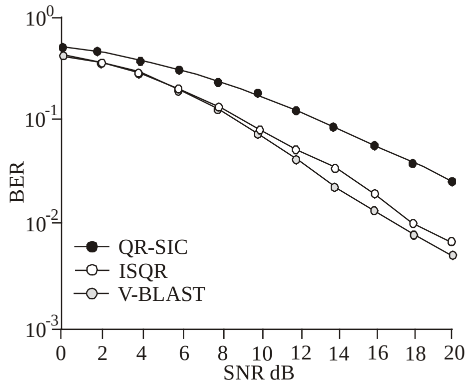

Fig. 1: M = 4, N = 4, BER curve with ZF criteria

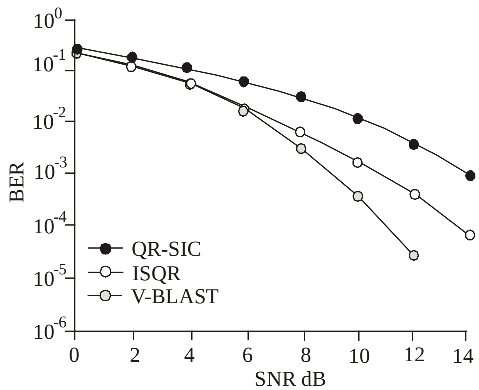

Fig. 2: BER curve with ZF criteria under M = 6, N = 8 MIMO system

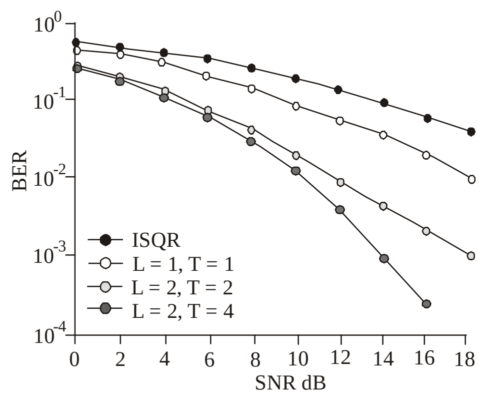

Fig. 3: BER curves in M = 4, N = 4 MIMO system with QPSK modulation

SIMULATION EXPERIMENTS

In the computer simulation, we consider a MIMO antenna system. Channel is assumed to be independently Rayleigh faded and quasi-static. Under correlated channels, ZF criteria are used at the receiver side. Following in the previous discussion, the performance is measured in term of BER for a frame of 1000 bits from QPSK constellations averaged over 100 frames. We compare detection performance of

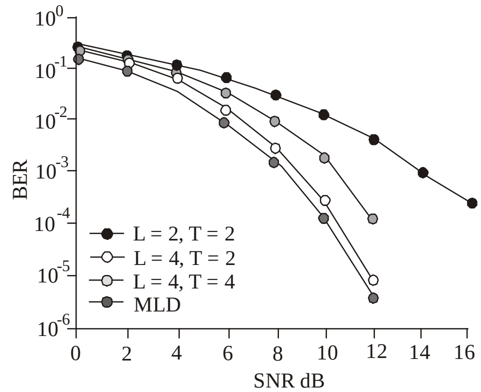

Fig. 4: BER curves in M = 4, N = 4 MIMO system with 16-QAM modulation

proposed sorting method with QR-SIC and V-BLAST. The BER curves are verified in Fig. 1 and 2.

Figure 1 shows the performance of various detection algorithms with M = 4, N = 4, antennas MIMO system. As expected, the ISQR algorithm's performance near that of V-BLAST and outperform OSIC algorithm. Comparing with V-BLAST, its complexity is much lower.

Figure 2 shows the performance with M = 6, N = 8, antennas MIMO system. The advantage of the proposed algorithm becomes obviously with the increasing number of antennas.

Figure 3 presents the BER performance in case of L = 1, T = 2; L = 2, T = 2; L = 2, T = 4; and QPSK modulation comparing with MLD. When, L = 1, T = 1, the proposed algorithm equivalent to OSIC.

Figure 4 shows the BER performance in case of L = 2, T = 2; L = 4, T = 2; and L = 4, T = 4 with 16-QAM. When L at the same value, the performance better with T increasing. With the increasing of the 2 parameter, the detection performance is close to that of ML detection and the calculating complexity is much lower than ML detection. The trade-off performance can be adjusted by setting L and T at different value. The bigger of value, the performance more close to ML detection with increasing complexity.

Calculating complexity analysis: Comparing with V-BLAST and QR-SIC, ISQR algorithm needs 2 times QR decomposition and the second QR decomposition is performed with upper triangular matrix which has many 0 elements, so its complexity is still $O(M)^3$, a little higher than QR-SIC and much lower than that of V-BLAST, which complexity is $O(M)^4$.

Using ISQR in SIC, the proposed algorithm performs P layers ML detection, calculating and sorting the partial accumulated metrics, selecting L partial sequences with smaller partial accumulated metrics to do SIC detection, so its complexity will change with parameters P and L. The detail can be summarized as:

Calculating in ML detection of P layers is:

$$f_{\text{ML-P}} = q^P N(M+1) \tag{14}$$

where,

q = The order of modulation
P = The number of layers to be performed ML detection
M = The number of transmitted antennas
N = The number of receiver antennas

Calculating of SIC is expressed as:

$$f_{\text{SIC}} = 12M^2 N + 4M^2 + 6MN + 3M \tag{15}$$

So after selecting L partial consequences, the complexity of performing SIC is:

$$f_{\text{SIC-L}} = L \times [12(M-P)^2 N + 4(M-P)^2 + 6(M-P)N + 3(M-P)] \tag{16}$$

where,
L = the number of sequences to perform SICS detection.

The total calculating is:

$$\begin{aligned} f_{\text{proposed}} &= f_{\text{ML-P}} + f_{\text{SIC-L}} \\ &= q^P N(M+1) + L \times [12(M-P)^2 N \\ &\quad + 4(M-P)^2 + 6(M-P)N + 3(M-P)] \end{aligned} \tag{17}$$

When P is changeless, the complexity is increasing linearly with parameter L and, when L is changeless, the complexity will increase exponentially with parameter P. So the calculation and performance can be trade-off by setting parameters P and L at different values.

CONCLUSION

Based on the rule of maximum SNR, ISQR algorithm has been proposed here. The optimal detection sort could be provided by ISQR like that of V-BLAST with little calculation. Using this method and inspiring by the idea of MLD, an improved detection scheme has been proposed in this study also. The channel is decomposition by ISQR, searching layers with MLD at the first step with the first parameter, then the partial accumulated metrics are calculated and sorted, partial candidate sequences are selected with the second parameter, successive interference cancellation detection algorithm is performed to detect the left layers parallel, the symbol with the minimum accumulated metrics would be quantized as the transmitted signal finally. By setting different values for the 2 parameters, the trade-off between detection performance and computing complexity has been obtained properly.

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