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Sphere Decoding and OSIC Group Interference Suppression Detection Algorithm based on Adaptive Modulation

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Abstract: Due to coordination of performance and complexity in multiple-input multiple-output system at the same time, this paper proposes a group interference suppression detection algorithm sphere decoding ordered successive interference cancellation (SD-OSIC) based on adaptive modulation. It adopts the strategy of group detecting, the signal with high Signal to Noise Ratio (SNR) is detected by Sphere Decoding (SD) algorithm instead of the maximum likelihood one and the rest of the signal is detected by Ordered Successive Interference Cancellation (OSIC). Nevertheless, it also takes the receiving SNR as a parameter to modulate the transmitting signal adaptively. The simulation results show that the SD-OSIC detection based on adaptive modulation can achieve higher spectrum efficiency than fixed modulation as well as having a performance.

Key words: MIMO system, adaptive modulation, sphere decoding algorithm, ordered successive interference cancellation algorithm

INTRODUCTION

Multiple-input multiple-output (MIMO) system is a new generation of wireless communication system, it implies multiple antennas technology both at transmitting and receiving terminal to enhance spatial degree of freedom and it can increase the transmission reliability as well as spectrum efficiency. MIMO includes two kinds of applications: one is the spatial multiplexing system that is designed to improve transmission rate, the other is the space-time coding system that is designed to improve transmission reliability (Lupas and Verdu, 1989). In spatial multiplexing system, the Vertical-Bell Labs Layered Space-Time (V-BLAST) structure (Woliansky *et al*., 1998) has an vast potential for application due to using the simple corresponding relationship between data streams and antennas. It obtains high spectral efficiency by dividing the incoming data into multiple substreams and transmitting each substream on a different antenna. However, because the channel correlation between multi-antennas will seriously affect the system performance, the research hotspot is focused on transmitting pre-coding and detection algorithm in correlated channel.

In the aspect of detection algorithm in V-BLAST system, although Maximum Likelihood (ML) detection can obtain the optimal decoding performance, it's difficult to apply in actual system because its decoding complexity increases exponentially with antenna numbers and modulation constellation size (Lupas and Verdu, 1989). The Ordered Successive Interference Cancellation (OSIC) algorithm proposed by Golden *et al*. (1999) is able to reduce the complexity but serious error propagation affects the other symbols detected later. And the performance of V-BLAST system using OSIC receiver in correlated channel is analyzed by Feng *et al*. (2011). In order to reduce the influence of error propagation, a ML-OSIC group interference suppression detection algorithm divide the symbols into two part, the symbol with high signal-to-noise ratio (SNR) is firstly detected by ML and then the rest is detected by OSIC. As a result, it is not only reducing the research time of ML algorithm but also suppressing the interlayer interference and error propagation (Lan *et al*., 2008). Duan and Guo (2011) proposed a linear dispersive space-time-frequency code with Parallel Interference Cancellation (PIC) group decoding, which obtain the similar diversity gain as the ML decoding. Combining the Sphere Decoding (SD) algorithm and the sequential detection method, an Adaptive Group Detection (AGD) scheme for V-BLAST architectures is proposed by Jing *et al*. (2009). It can achieve a very flexible tradeoff between the performance and complexity by adjusting the group parameter. An efficient Group Sphere Decoding (GSD) algorithm is proposed by Yang *et al*. (2007). This method utilizes a channel-based group detection strategy. The transmitted symbols on each substream are detected by SD within each group and SIC between groups. An adaptive group detection algorithm. Jing and Zhou (2008) proposed by

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comparing the post-detection SNRs with the group thresholds, the sensitive symbol subgroup is detected by SD algorithm.

In this study, the SD-OSIC multi-user detection algorithm based on adaptive modulation is proposed on basis of ML-OSIC algorithm. It uses SD algorithm (Viterbo and Boutros, 1999) with lower complexity instead of ML algorithm. This innovation can achieve the balance between algorithm performance and implementation complexity by making full use of channel resource under adaptive modulation.

In this paper, the following notations will be used:

- $(.)^T$ denotes the transpose operation of a matrix
- $(.)^H$ denotes the conj-transpose operation of a matrix
- $(.)^+$ denotes the Moore-Penrose pseudoinverse operation of a matrix

SYSTEM MODEL

A V-BLAST system with M transmit antennas and N receive antennas is considered. Transceivers at both terminals use regular arranged uniform linear antenna array. The channel model is transmitting correlation only and showing as Fig. 1. The received signal model can be written as:

$$r = Hs + n = \sum_{i=1}^{M} h_i s_i + n \qquad (1)$$

where r is the received signal vector at a certain time, s is the M dimension vector of the transmitted signal, H is the N×M channel matrix in complex field, its elements h_{ij} (i = 1,..., N, j = 1,...,M) represents the channel fading coefficient between the jth transmitting antenna and the ith receiving antenna, n is the N dimension vector of white complex Gaussian noise with zero-mean.

At the transmit terminal, the input signal s is converted into sub data stream for M path by serial-parallel conversion. Then the adaptive modulation format is chosen according to the feedback command from receiving terminal. At the receiving terminal, SD and OSIC joint detection algorithms are used to separately detect the different transmitting signals in turn. Finally, the sub data stream for M path at receiving terminal is converted into the final output signal vector $\hat{S}$ through parallel-serial conversion. The next section will introduce the adaptive modulation, SD decoding and OSIC algorithm, respectively.

ADAPTIVE MODULATION TECHNOLOGY BASED ON CHANNEL STATUS INFORMATION

Each sub channel has different channel coefficient due to channel fading and channel correlation. In order to making full use of wireless channel resource, adaptive modulation is introduced in wireless transmission process. That is to say, the receiver RF link will calculate the SNR of each transmitting sub channel according to the channel estimation, then the highest modulation mode is figured out under the condition of meeting the target Bit Error Rate (BER). The result is informed to the transmit terminal through wireless feedback Dedicated Physical Control Channel (DPCCH), so that it can adopt the appropriate modulation mode in the next frame transmission. These measures could be effective in the slow fading channel.

The adaptive modulation procedure of the jth transmitting sub channel is listed in Fig. 1:

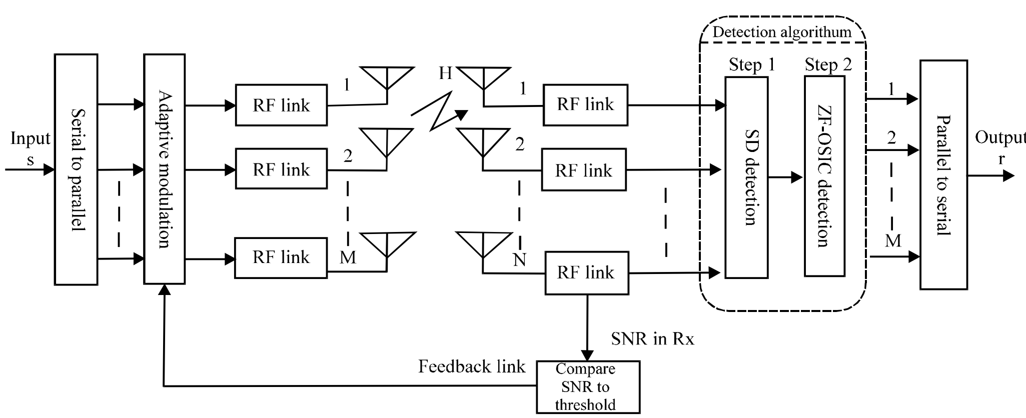

Fig. 1: MIMO system block diagram with adaptive modulation, SD: Sphere Decoding, M: Transmit antennas number, N : Receive antennas number, H: N×M channel matrix, ZF-OSIC: Zero forcing ordered successive interference cancellation

Calculate the symbol SNR ρ_j of the jth transmitting channel based on Zero Forcing (ZF) criterion according to the receiving channel matrix obtained by channel estimate. The unit of ρ_j is dB:

$$\rho_j = 10\lg\left[\frac{p}{(\sigma\|G_j\|_2)^2}\right] \quad (2)$$
$$\|G_j\|_2 = \|H_j^+\|_2$$

where, p is the default system bit power, σ is the noise variance, H_j^+ represents the jth row vector of H^+ and $\|.\|_2$ represents the 2-norm of vector:

- Calculate a series of the minimum bit SNR ρ_m corresponding to various modulation types which satisfy the needs of target BER, as formula (3). The bit number per symbol of each modulation mode is m∈[1,2,…,Φ]; Φ is the bit number per symbol of the maximum modulation mode (such as: 4 QAM modulation, Φ = 2):

$$BER_{qam}(m,\rho_m) = \frac{4}{m}\beta\left(\sqrt{\frac{3m\rho_m}{(2^m-1)}}\right) \quad (3)$$

Where:

$$\beta(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2}dt$$

- Compare ρ_j and a series of SNR threshold calculated by formula (3), finding the maximum value of m that satisfies $\rho_j \geq \rho_m$. In this process, if the compared data result turns to be zero, which is less than the minimum SNR threshold of BPSK modulation, then data will not be transmitted. The result value is going to be feedback to the transmit terminal in order to determine the modulation mode on the jth antenna

SPHERE DECODING (SD)

At the receiving terminal, sphere decoding algorithm aims at solving the following problem: $\min_{s\in\Omega\subset Z^m}\|r-Hs\|_2$, in which the Z^m is the whole integer lattice set based on ML, Ω is the lattice set of initial radius d_s and s is the transmitting signal. The optimum point set must satisfy:

$$\|r-Hs\|_2^2 \leq d_s^2 \quad (4)$$

Due to the presence of noise influence, the signal point will disturb around the lattice. Thus the initial search radius d_s should be chosen with some redundancy (Chen *et al*., 2008):

$$d_s = \alpha*(2N)*\sigma^2 \quad (5)$$

In this formula, the real scaling coefficient α = 3 is an experienced value, N is the number of receiving antennas and σ is the noise variance.

SD algorithm is based on QR decomposition, in which:

$$H = [Q_1, Q_2]\begin{bmatrix}R \\ 0_{(N-M)*M}\end{bmatrix}$$

The matrix Q_1 and Q_2 represent the first M and N-M orthogonal columns, respectively, R is the M×M dimension upper triangular matrix. The:

$$H = [Q_1, Q_2]\begin{bmatrix}R \\ 0_{(N-M)*M}\end{bmatrix}$$

Is substituted into formula (4):

$$d'^2 = d_s^2 - \|Q_2^H y\|_2^2,\ y = Q_1^H r \quad (6)$$

where d′ is the first iterative of initial radius d_s, then substitute the formula (6) into (4):

$$\|y-Rs\|_2^2 \leq d'^2 \quad (7)$$

Next step is expansion the formula (7) based on the definition of vector 2-norm:

$$d'^2 \geq \sum_{i=1}^{M}\left|y_i - \sum_{j=i}^{M}R_{i,j}s_j\right|^2 \quad (8)$$

In the formula above, y_i is the ith element of vector y, $R_{i,j}$ is the ith row and jth column element of the upper triangular matrix R and s_j is the jth element of vector s. The important condition for the establishment of formula (8) will be:

$$d'^2 \geq |y_M - R_{M,M}S_M|^2$$

As a result, the value of decoding output S_M can be calculated as:

$$\frac{-d'^2 + y_M}{R_{M,M}} \leq s_M \leq \frac{d'^2 + y_M}{R_{M,M}} \quad (9)$$

Using the recursive formula:

$$d'^2 - |y_M - R_{M,M}s_M|^2 \geq |y_{M-1} - R_{M-1,M}s_M - R_{M-1,M-1}s_{M-1}|^2$$
$$\left[\frac{-d_{M-1} + y_{M-1|M}}{R_{M-1,M-1}}\right] \leq s_{M-1} \leq \left[\frac{d_{M-1} + y_{M-1|M}}{R_{M-1,M-1}}\right] \quad (10)$$

where d_{M-1} is the radius recursive by d′ through formula (10) and $y_{M-1|M}$ is obtained by Y_M through formula (9) , S_M, S_{M-1}... S_1 will be calculated in turn and the complete set solution $\{S_M, S_{M-1}...S_1\}$ is obtained.

Based on the above analysis, a conclusion can be drawn that sphere decoding is a circular searching process. since the above steps are mainly for the field of real numbers, the complex signal should be converted into real form if the M_QAM modulation is adopted in this paper. It can be represented as follows (Zhang *et al.*, 2009):

$$\begin{bmatrix} Re\{r\} \\ Im\{r\} \end{bmatrix} = \begin{bmatrix} Re\{H\} & -Im\{H\} \\ Im\{H\} & Re\{H\} \end{bmatrix} * \begin{bmatrix} Re\{s\} \\ Im\{s\} \end{bmatrix} + \begin{bmatrix} \begin{pmatrix} Re\{n\} \\ Im\{n\} \end{pmatrix} \end{bmatrix} \quad (11)$$

ALGORITHM FLOW

To sum up, the SD-OSIC algorithm based on adaptive modulation is as follows:

Step 1: Initialization settings: transmitting vector s and independent channel matrix vector H. R_t is the N×N transmit correlation matrix, the correlated channel model H_{corr} will be:

$$H_{corr} = HR_t^{1/2}$$

Step 2: Take the computing process from step 1-3 in section ADAPTIVE MODULATION TECHNOLOGY, determine the modulation mode of transmit terminal and the bit number of transmitting data

Step 3: Order and group the H_{corr} according to the SNR:

- Ordering:

$$G = H_{corr}^{+} \left\|(G)_{n_1}\right\|_2^2 \le \left\|(G)_{n_2}\right\|_2^2 \ldots \left\|(G)_{n_M}\right\|_2^2$$

$(n_1, n_2....n_M)$ is the subscript permutation after ordering the row vector of G

- H_{corr} is divided into H_1 and H_2 according to the group criterion:

$$H_{corr} = [H_1, H_2] = [(h_1, h_2..., h_k)(h_{k+1}, h_{k+2}, ..., h_M)]$$

Step 4: SVD decomposition, interference suppression of the M-K groups of symbol:

$$H_2 = U\sum V^T$$

Multiply the formula r = Hs+n by W at both sides:

$$Wr = WHs+Wn$$

W is the matrix composed of a set of orthogonal vectors chosen in the null space of H_2: $WH_2 = 0$. 0 is the all-zero matrix. So the following equation can be got:

$$\hat{r} = \hat{H}\hat{s}_{1...K} + \hat{n}, \hat{H} = [Wh_1, Wh_2, ..., Wh_K], \hat{n} = Wn$$

Step 5: SD decoding for the first K sub streams: Repeat process from the formula (4-10), obtain the complete solution set $\hat{s} = \{s_M, s_{M-1}, \ldots, s_2, s_1\}$

Step 6: Cancel the interference, OSIC detection from the (K+1)th to the Mth sub stream:

$$\tilde{r} = r - \hat{H}*\hat{s}$$

Circulating detection:

- **Initialize:** i = 1, $r\_osic = \tilde{r}$, $G_i = (H_2)^+$, $k_i = \arg(\min\|(G_i)_{j\bullet}\|_2^2)$, where $(G_i)_{j\bullet}$ is the jth row vector of matrix G_i
- **Interference suppression:** i = 1:M-K
  $w_{ki} = (G_i)_{j\bullet}$, $y_{ki} = w_{ki}$, $\hat{s}_{k_i} = D(y_{k_i})$
  where, D(.) represents the hard-decision of y_{ki}
- Cancel the interference:
  $r' = r' - \hat{s}_{k_i}(H_2)_{\bullet k_i}$, $I \leftarrow i+1$
  $G_{i+1} = (H^+_2)$. $k_{i+1} = \arg\min\|(G_{i+1})_{j\bullet}\|_2^2$

where, $()_{\bullet ki}$ is the kth_i column of the matrix.

ALGORITHM COMPLEXITY ANALYSIS

The ML-OSIC and SD-OSIC algorithm discussed in this paper both belong to the group interference suppression algorithm. Their complexities can be divided into two parts, one part is the complexity of ML or SD algorithm, the other part is the complexity of OSIC. We focus on the first part because the second part is same. Generally speaking, the complexity of algorithm can be measured by searching times.

The traditional ML algorithm uses the exhaustive traversal searching, the cycle index of the core part will increase exponentially by M and Φ, its complexity turns out to be $2^{\Phi M}$ (Wang and Zhu, 2009).

SD algorithm has the similar principle of ML, however, it does not have to search the entire lattice. We only need to search in a multidimensional sphere with radius d_s. In this sphere, the lattice nearest to r is also the maximum likelihood point. Through the flow of SD algorithm in above section we can infer that each element value of s is determined by dimensional recursive according to searching radius and the range of s. As a result, its complexity is in proportion of access points of each dimension (Lan *et al.*, 2008). The SD algorithm decreases the number of searching points in each dimension through limiting or reducing initial radius. If the initial radius is appropriate, we can access to all the solution set of *s* so as to reduce the algorithm complexity; otherwise, we need to expand the radius until obtain the complete s. Thus, with the increase of initial radius and access points in each dimension, the complexity of sphere decoding algorithm will gradually approach to the ML algorithm. In this study, we mainly reduce the computing complexity of SD algorithm by choosing appropriate searching range.

For the OSIC algorithm, because interference of the first K column signals has been canceled, the detection of M-K column signals will be detected by interference cancellation strategy in turn. The cycle number of core algorithm will be M-K times.

In short, compared to the ML-OSIC algorithm proposed (Yang *et al*., 2004), the SD-OSIC algorithm uses the SD algorithm to narrow searching range during detecting the symbol with higher SNR, it turns out to reduce complexity of algorithm.

SIMULATION

In this section, we use a 4×4 V-BLAST system as the simulation model and the modulation mode includes BPSK, 4 QAM, 16 QAM and 32 QAM. We first assume only transmit correlation is present and the receiver know the channel state information totally through channel estimated. We adopt the GWSSUS correlated channel model (Gore *et al*., 2002) and the transmit correlation matrix R_t is:

$$R_t = \begin{bmatrix} 1 & 0.57e^{-2.25j} & 0.17e^{0.02j} & 0.29e^{2.94j} \\ 0.57e^{2.25j} & 1 & 0.57e^{-2.25j} & 0.17e^{0.02j} \\ 0.17e^{-0.02j} & 0.57e^{2.25j} & 1 & 0.57e^{-2.25j} \\ 0.29e^{-2.94j} & 0.17e^{-0.02j} & 0.57e^{2.25j} & 1 \end{bmatrix} \quad (12)$$

Simulation experiment 1: Comparison of performance and complexity.

The simulation uses the strategy of interference suppression by average packet under the 4×4 system which using 4 QAM modulation. It uses the ZF, SD and ML to detect the first two sub channels and uses the OSIC to detect the rest. Simulation results illuminate that: in the aspect of bit error performance (Fig. 2), the performance of SD-OSIC lies between ZF-OSIC and ML-OSIC and approach ML-OSIC in BER comparison. But in the aspect of complexity (Fig. 3), the simulation times of SD-OSIC and ZF-OSIC are apparently only 20% of that of ML-OSIC. the conclusion can be drawn based on the Fig. 3.

Simulation experiment 2: Comparison of spectrum efficiency with and without adaptive modulation.

In this part the spectrum efficiency of SD-OSIC algorithm based on fixed modulation and adaptive

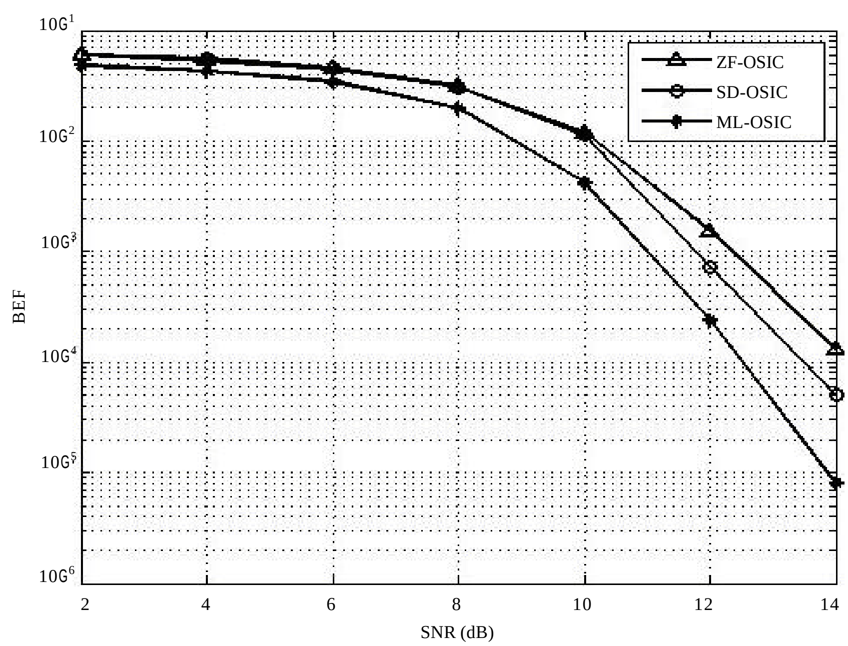

Fig. 2: Comparison of bit error rate performances of three algorithms

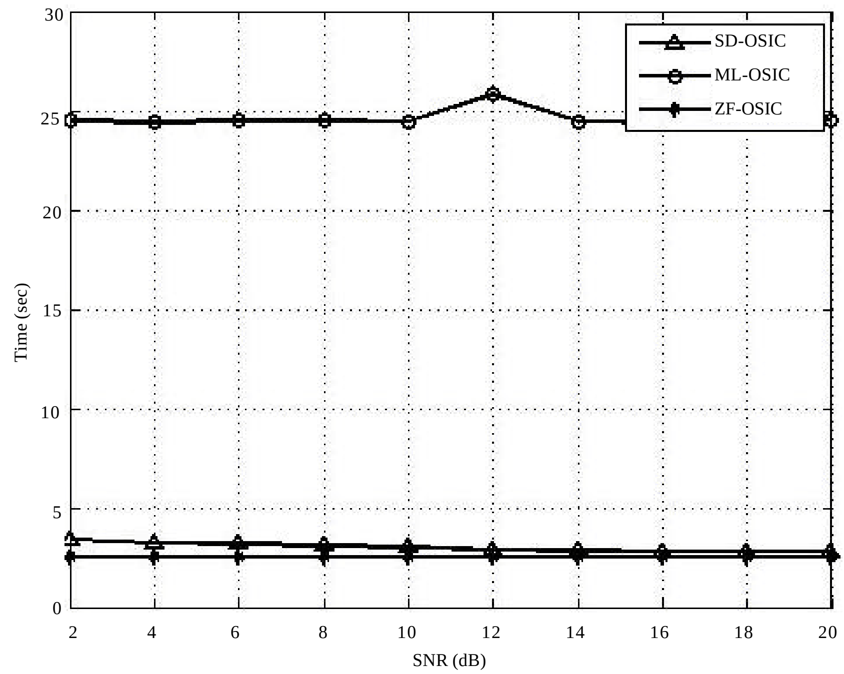

Fig. 3: Comparison of simulation time complexities of three algorithms

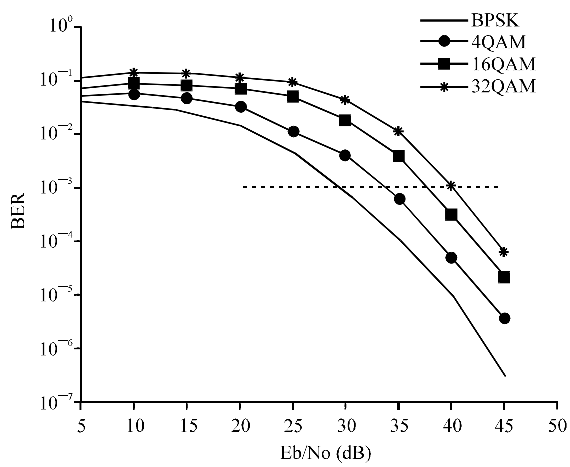

Fig. 4: The SNR threshold corresponding to different modulation modes

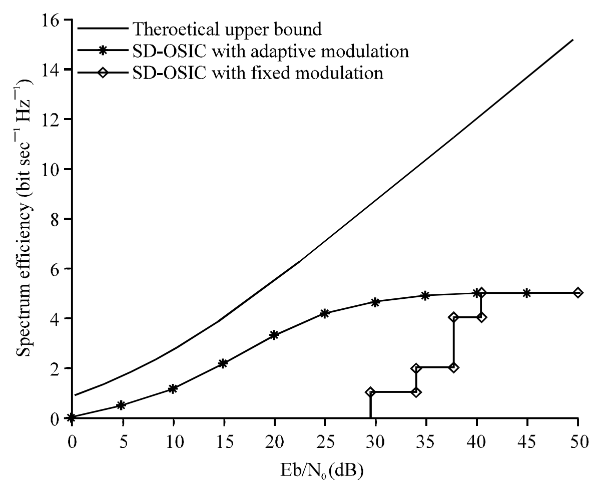

Fig. 5: Comparison of SD-OSIC with adaptive modulation or fixed modulation

modulation was compared, set the target BER of 10^{-3} and use the formula (11) as the transmit channel correlated matrix. In Fig. 4, the simulation results show that the minimum BER threshold (modulation modes) will be 29 dB (BPSK), 34 dB (4 QAM), 38 dB (16 QAM) and 44 dB (32 QAM), respectively. It means that a higher-order modulation mode can be used at the transmit terminal if the channel condition is better and the receiving SNR is higher. Therefore, the spectrum efficiency curve of SD-OSIC algorithm based on fixed modulation can be drawn as Fig. 5 the spectrum efficiency turns out to be zero when E_b/N_0<29 dB, which means the average SNR of each subchannel can not achieve the minimum threshold value of BPSK at all.

The spectrum efficiency of SD-OSIC algorithm with adaptive modulation is a gently rising curve. For sub channel with lower SNR, a lower modulation mode or even not transmit symbols is employed to avoid the interference between channels, meanwhile, more energy are allocated to the other channels with better quality.

Thereby, thanks to the adaptive modulation, the overall spectrum efficiency of MIMO system will be improved.

This study uses the SD detection algorithm instead of ML in the group interference suppression. This new algorithm replaces the exhaustive searching range by the one within a radius of sphere decoding. It will result in not only a significant reduction of computing complexity but also a less evident performance degradation. By means of feedback SNR from the receiver to the transmitter, adaptive modulation are employed to improve the spectrum efficiency and against the transmit correlation. This method can ensure that the higher modulation mode are used and more bits are transmitted in sub channel with better status.

CONCLUSION

This study proposes the SD-OSIC detecting algorithm with adaptive modulation. On the one hand, SD algorithm is used to reduce the decoding complexity; on the other hand, adaptive modulation is introduced to increase the spectrum efficiency. In a 4×4 V-BLAST system, the complexity of this algorithm is only 20% of that of ML-OSIC. It also has up to 3 bit sec^{-1} Hz^{-1} higher spectrum efficiency than SD-OSIC algorithm with fixed modulation when the target bit error rate is 10^{-3}.

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