MIMO System을 위한 Path Metric 비교 기반 적응형 *K*-best 알고리즘

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An Adaptive *K*-best Algorithm Based on Path Metric Comparison for MIMO Systems

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요 약

Adaptive *K*-best 검출 방식은 MIMO system을 위해 제안된 알고리즘이다. 제안된 방식은 각 *K*-best 단계에서 Zero-Forcing(ZF) 추정치의 신뢰도의 정도를 기반으로 하여, 생존 path들의 개수인 *K*값을 바꾸는 방식이다. 고정된 *K*값을 사용하는 *K*-best 방식의 치명적인 단점은 잘못된 ZF 추정치에 의해 발생하는 불완전한 간섭 제거로 인해 올바른 path임에도 일시적으로 그 거리가 *K*개의 최소 path 거리들 보다 더 커질 수 있다. 잘못된 ZF 추정치가 발생된 경우에는, path들 간의 거리들이 뚜렷하게 다르지 않다는 것을 관찰을 통해 발견하였다. 본 논문에서는 ZF 추정치의 신뢰도를 나타내는 지표로, 최소값을 갖는 path의 거리와 두 번째 최소값을 가지는 path 거리의 비를 사용한다. 최소값을 가지는 두 path의 거리의 비를 근거로, *K*값을 적절하게 선택하는 제안된 방식은 기존의 고정된 *K* 값을 사용하는 *K*-best 방식에 비해, 확연히 개선되었음을 보여준다. 제안된 방식은, 큰 *K*값을 사용하는 방식에 비해 평균 계산양은 매우 작으면서, 큰 *K*값을 사용한 방식의 성능을 가진다.

Key Words : MIMO system, Tree search, Adaptive *K*-best

ABSTRACT

An adaptive *K*-best detection scheme is proposed for MIMO systems. The proposed scheme changes the number of survivor paths, *K* based on the degree of the reliability of Zero-Forcing (ZF) estimates at each *K*-best step. The critical drawback of the fixed *K*-best detection is that the correct path's metric may be temporarily larger than *K* minimum paths metrics due to imperfect interference cancellation by the incorrect ZF estimates. Based on the observation that there are insignificant differences among path metrics (ML distances) when the ZF estimates are incorrect, we use the ratio of the minimum ML distance to the second minimum as a reliability indicator for the ZF estimates. So, we adaptively select the value of *K* according to the ML distance ratio. It is shown that the proposed scheme achieves the significant improvement over the conventional fixed *K*-best scheme. The proposed scheme effectively achieves the performance of large *K*-best system while maintaining the overall average computation complexity much smaller than that of large *K* system.

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Ⅰ. Introduction

Nowadays, Multiple-input multiple-output (MIMO) wireless communication system has received significant attention, due to the rapid development of high-speed broadband wireless communication systems employing multiple transmit and receive antennas. The theoretical results show that MIMO systems can provide enormous capacity gains, since multi-antenna communications allows for information transmission at very high rates. The major issue of concern is to keep the computational complexity of the decoding algorithm within reasonable bounds. Zero-Forcing (ZF) and Minimum Mean Square Error (MMSE) are simple detection algorithm that linearly estimate the transmitted signals. Vertical Bell Laboratories Layered Space-Time (V-BLAST) is a well known non-linear detection algorithm using symbol cancellation [3]. Maximum Likelihood Detection (MLD) with Euclidean distance is another non-linear detection algorithm, which achieves the theoretical optimal performance among various MIMO detection algorithms. However, MLD requires exponential complexity refer to the number of transmit antennas.

We need to reduce the computational complexity of the MLD algorithm for practical implementation of MIMO system. The *K*-best algorithm (or *M*-algorithm) overcomes the exponential complexity problem of the MLD algorithm because it makes the complexity become proportional to the number of transmit antennas [1][2][4][5]. Even though, it has the irreducible errors from the selected path metric crossing. In [1][2], they proposed combining ZF and *K*-best algorithm (the ZF *K*-best algorithm hereafter) for MIMO systems[1][2]. It used the estimates from ZF to supplement the path metric crossing problem of the *K*-best algorithm. However, there is a performance boundary of the ZF *K*-best algorithm due to the incorrect estimates from ZF. If the performance of the ZF *K*-best algorithm approaches to that of the MLD, it requires a very large number of survivor paths *K*, which causes the computational complexity to approach to the complexity of the MLD [1][2].

The conventional variable *K*-best algorithm adaptively controls *K* in accordance with the measured SNR value [8]. Therefore, this algorithm can complement the drawback of the fixed *K*-best scheme. However, this algorithm can not adaptively change *K* against the instantaneous variation of the channel condition since this algorithm controls *K* based on the average noise power, which is the main drawback of these algorithms.

In this paper, we propose an adaptive *K*-best algorithm which adaptively changes *K* according to the accuracy of the estimates from ZF. For the case when the minimal ML distance among all possible paths is much smaller than the second minimal one, which means that the channel environment is good and the estimates from ZF are reliable, we decrease the value of *K*. In the reverse case, *K* should be increased in order not to miss correct path in the possible candidate set. The proposed adaptive *K*-best algorithm achieves significantly improved performance compared to the conventional *K*-best algorithm and approaches the performance of the MLD with much lower computational complexity. The remainder of the paper is organized as follows: The section II describes the basic MIMO system considered in this paper and the section III explains the conventional detection algorithms. The proposed adaptive *K*-best algorithm is introduced in the section IV. In the section V, the performance of the proposed algorithm is evaluated through computer simulations. Finally, we present the conclusion in the section VI.

Ⅱ. MIMO System

We consider a MIMO system which consists of N transmit and L receive antennas. The system can be described by:

$$\boldsymbol{x} = \boldsymbol{H}\boldsymbol{s} + \boldsymbol{n} \tag{1}$$

where $\boldsymbol{s}$ is the N dimensional transmit vector, each element of which is chosen from a (complex-valued) constellation, $\boldsymbol{H}$ is the $L\times N$ complex channel matrix, $\boldsymbol{x}$ is received vector, and $\boldsymbol{n}$ is an L dimensional complex AWGN vector. We assume Rayleigh fading where the elements of $\boldsymbol{H}$ are independent complex Gaussian. We assume that the channel matrix $\boldsymbol{H}$ is known by the receiver and remains constant over the data symbol duration.

Ⅲ. Conventional Signal Detection Algorithms

3.1 Zero-forcing Linear Detection

The Zero-forcing (ZF) front-end is given by :

$$\tilde{\boldsymbol{s}} = \boldsymbol{H}^{+}\boldsymbol{x} \tag{2}$$

where $\boldsymbol{H}^{+} = (\boldsymbol{H}^{H}\boldsymbol{H})^{-1}\boldsymbol{H}^{H}$ denotes the pseudo inverse of the channel matrix $\boldsymbol{H}$ and $\boldsymbol{H}^{+}$ denotes the Hermitian conjugate. Each element of $\hat{\boldsymbol{s}}$ is then sliced to the nearest constellation point of possible transmitted signals. Thus, the ZF algorithm obtains detected signal $\hat{\boldsymbol{s}}$ by slicing $\tilde{\boldsymbol{s}}$. However, noise enhancement in $\tilde{\boldsymbol{s}}$ results in a significant performance degradation.

3.2 Maximum Likelihood Detection

The Maximum Likelihood Detection (MLD) performs vector decoding and is optimal in the sense of minimizing the error probability. The MLD evaluates the Euclidean distance between the received symbol vector $\boldsymbol{x}$ and replicated symbol vectors $\boldsymbol{H}\boldsymbol{s}_i$ and then, the estimate of the transmitted signal vector is determined as follows:

$$\hat{\boldsymbol{s}} = \arg\min_{\boldsymbol{s}_i} \left\| \boldsymbol{x} - H\boldsymbol{s}_i \right\|^2 \tag{3}$$

where the minimization is performed over all possible transmit vector symbols $\boldsymbol{s}_i$'s. We let M_C denote the number of constellation points for each transmit antenna, a brute force implementation requires an exhaustive search over a total of $M_C^{\;N}$ vector symbols making the decoding complexity of this detection increase exponentially in the number of transmit antennas.

3.3 K-best Algorithm

The K-best algorithm is based on a tree search decoding technique. It has been extensively studied because this algorithm reduces the computational complexity of the MLD with approach to the MLD performance. Let us rewrite (3) as:

$$\hat{\boldsymbol{s}} = \arg\min_{\boldsymbol{s}_i} \left\| \boldsymbol{x} - \sum_{j=1}^{N} H_j s_{ij} \right\|^2 \tag{4}$$

where $\boldsymbol{H}_j$ is the j-th column of $\boldsymbol{H}$, and s_{ij} is the j-th component of vector $\boldsymbol{s}_i$, and if the components of $\hat{\boldsymbol{s}}$ are estimated one after another it is seen that the MLD algorithm is related to sequence estimation. The metric of tree search is defined by :

$$\mu(\boldsymbol{s}_i^{[n]}, n) = \arg\min_{\boldsymbol{s}_i^{[n]}} \left\| \boldsymbol{x} - \sum_{j=1}^{n} H_j s_{ij}^{[n]} \right\|^2, n \geq 1 \tag{5}$$

where n is the step count of the tree search process; $\boldsymbol{s}_i^{[n]}$ is the n-dimensional partial vector of possible signal candidates at the n-th step node, $\boldsymbol{s}_{ij}^{[n]}$ is the j-th element of $\boldsymbol{s}_i^{[n]}$. With the conventional K-best algorithm, only K partial vectors for survive among possible sets of vectors using the metric, as shown in fig. 1. At each step n, the K-best algorithm has a list of K nodes in the tree. For each node in the list, the algorithm calculates the norms of its sub-nodes according to Eq.(5). Of the KM_C resulting norms, the K-best are put in the list and the corresponding nodes become the new survivors.

The complexity of this algorithm is linear in N. Note that the number of metric computations with the K-best algorithm is only $M_C+KM_C(N-1)$, whereas the MLD requires M_C^N. It has the additional advantage of a convenient implementation since its processing time is constant. However, the *K*-best algorithm cannot guarantee the survival of ML paths with overall possible candidates, because the metrics of the correct path can be temporarily larger than *K* smallest path metrics. This is because the remaining undetected symbols contribute to the received signal vector $\boldsymbol{x}$ as the correlated non-Gaussian interferences.

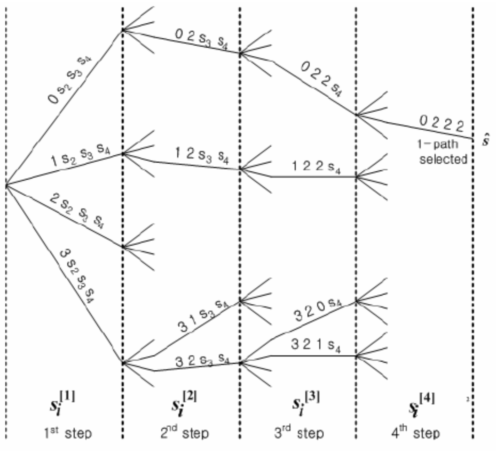

Fig. 1 Example of a search tree with *K*-best scheme. At each node, the best (*K*=4) paths are retained. Deleted paths are not shown. (with QPSK)

3.4 Combining ZF and *K*-best Algorithms

In [1], [3] they proposed the modified *K*-best algorithm. In the ZF *K*-best scheme, the ZF algorithm and the modified *K*-best algorithm are effectively combined. The most noticeable feature of the ZF *K*-best scheme is that the ZF algorithm improves the decoding accuracy of the original *K*-best algorithm. The ZF *K*-best algorithm system block diagram is shown in fig. 2. The Signal processing for the modified *K*-best block is described as follows. Instead of Eq. (5), the metric at the n-th step is given by:

$$\mu(\boldsymbol{s}_i^{[n]}, n) = \arg\min_{\boldsymbol{s}_i^{[n]}} \left\| \boldsymbol{x} - \left(\sum_{j=1}^{n} H_j s_{ij}^{[n]} + \sum_{j=n+1}^{N} H_j \hat{\boldsymbol{s}}_{j,ZF} \right) \right\|^2, n \geq 1 \quad (6)$$

Note that the rest of the partially estimated signal vector $\boldsymbol{s}_i^{[n]}$ is replaced by $\hat{\boldsymbol{s}}_{j,ZF}$, which is output by the ZF block. This is equivalent interference cancellation operation. The final estimate vector $\hat{\boldsymbol{s}}$ is given by :

$$\hat{\boldsymbol{s}} = \arg\min_{\boldsymbol{s}_i^{[N]}} \left(\mu'(\boldsymbol{s}_i^{[N]}, N) \right)^2, n \geq 1 \quad (7)$$

However, the ZF *K*-best algorithm also can not guarantee the survival of ML paths with all possible candidates, because the incorrect ZF detection causes incorrect interference cancellation introduces rather significant correlated non-Gaussian interference to the path metric calculation. If we want to make the performance of the ZF *K*-best algorithm approach to the MLD, we need very large value of *K*, however, the computational complexity will approach to that of the MLD. As a good trade-off for this problem, we propose the adaptive ZF *K*-best algorithm for the MIMO systems, where we adaptively change the number of *K* observing the path metrics at each step.

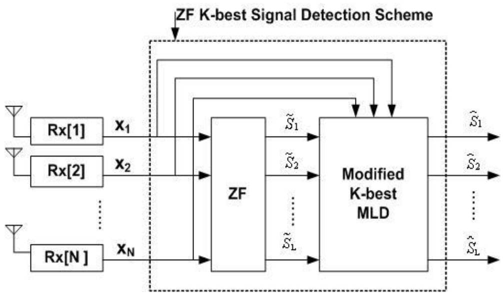

Fig. 2 System block diagram of the conventional ZF *K*-best algorithms

3.5 Conventional Variable *K*-best Algorithms

Fig. 3 illustrates the principle of the conventional variable *K*-best algorithm [8]. The conventional variable *K*-best scheme adaptively controls *K* in accordance with the estimated noise power (or SNR value). Therefore, this algorithm can complement the drawback of the *K*-best schemes by using fixed *K*. The threshold at the *n*-th step is calculated as

$$\triangle_n = \mu'_{(n,\min)} + X\sigma^2 \tag{8}$$

where $\mu'_{(n,\min)}$ is the minimum accumulated branch metric at the n-th step, X is a predetermined fixed value, and σ^2 is the measured noise power. The X value is a parameter that achieves a tradeoff between the computational complexity and the achievable SER. Therefore, the conventional variable *K*-best scheme reduce the complexity of the fixed *K*-best scheme method while maintaining close to optimal performance. However, this algorithm can not adaptively change *K* against the instantaneous variation of the channel condition since this algorithm controls *K* based on the average noise power, which is the main drawback of these algorithms. Simulation results in the section V reveals that this algorithm requires significantly higher complexity even with inferior error rate performance compared to the proposed adaptive scheme.

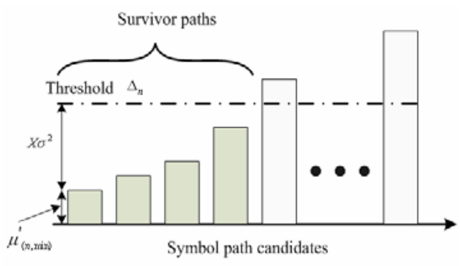

Figure 3. Example of the variable *K*-best based on the noise power.

Ⅳ. Proposed Adaptive *K*-best Algorithm

In this section, we will explain the proposed adaptive *K*-best algorithm. It consists of initial reordering, path metric (ML distance) computation and adaptive selection of K at each step. The system block diagram of the proposed scheme is shown in fig. 4. First, ZF block generates the initial estimate vector $\hat{\boldsymbol{s}}_{j,ZF}$ from the received signal vector $\boldsymbol{x}$, where the ZF block performs the same signal processing operation described in Section III-1.

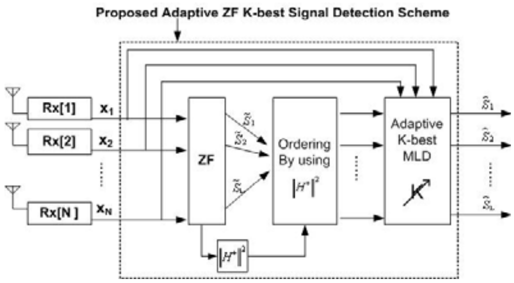

Fig. 4 System block diagram of proposed adaptive ZF *K*-best algorithms with ordering

Secondly, each column of matrix $\boldsymbol{H}$ and $\hat{\boldsymbol{s}}_{j,ZF}$ components are rearranged according to the order of $\|\boldsymbol{H}_j^+\|^2$, the norm of the pseudo inverse of $\boldsymbol{H}_j$ in the ZF block. This implies that we change the *K*-best detection order from the symbol with the lowest SNR to the symbol with highest SNR, which reduces the incorrect interference cancellation effect observed in the conventional ZF *K*-best algorithm.

After ordering, we employ *K*-best MIMO detection. The distinguishable feature of the proposed scheme is to adaptively change *K* based on, so-called reliability indicator for the ZF estimates at each step. In the first step of the *K*-best block, the number of M_C ML distance is computed and sorted. If the estimate from ZF is correct, the minimal ML distance is much smaller than the other ML distances. Otherwise, there is not so big difference among the minimal ML distance and the other ML distances due to the incorrect interference cancellation in the term $\sum_{j=n+1}^{N} H_j \hat{s}_{j,ZF}$ in Eq.(6). So, in the proposed scheme, we use the ratio of the second minimal ML distance to the minimal ML distance denoted by γ to check the ZF estimation reliability. In fig. 4, we show the CDF (Cumulative Distribution Function) of the ML distance ratio, γ with 16QAM, *Eb*/*No*=15dB with *N*=*L*=3 and *N*=*L*=4 system, respectively.

We can see that the ML distance ratio, γ for the case of incorrect ZF estimate is mainly distributed in the region of small values, $r \le 2$ in the fig. 5. On the other hand, the ML distance ratio, γ for the correct ZF estimate case is always larger than a certain threshold which is around 2 in fig. 4. From this observation, we conclude that the ML distance ratio, γ is a good indicator for the reliability of the ZF estimates. Consequently, the low ML distance ratio means the bad channel environment or inaccurately detected estimates from ZF and the high ML distance ratio means that the overall estimates detected by ZF are accurate. For the case when this ratio is large, that is, ZF estimation is reliable, we can successfully trace the correct path metric even with small *K*. On the other hand, for the case of small ratio, it is probable that the correct path metric deviates from the minimum value, which implies that we have to increase the possible candidates for the correct path, i.e., we have to increase *K*.

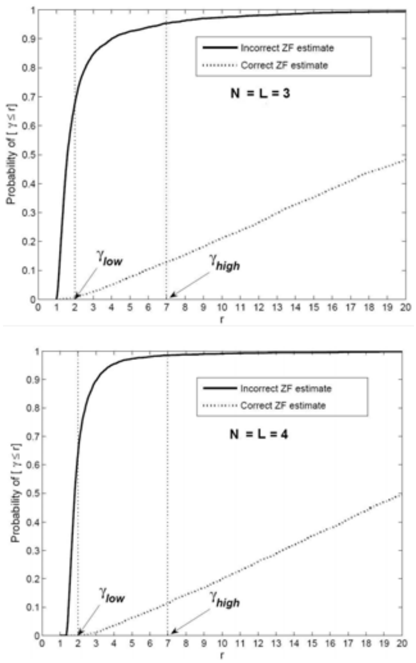

Fig. 5 The ML distance ratio (with 16QAM and Eb/No=15dB): The Cumulative Distribution Function of the second minimum ML distance to the first minimum ML distance ratio in each *K*-best step

The proposed adaptive *K*-best algorithm uses three valued *K* and adaptively change it according to ML distance ratio at each *K*-best step. Adaptation criterion is as follows :

1) If the ML distance ratio, γ is larger than γ_{high} : channel environment is good, accurate estimates from ZF detection $\Rightarrow$ set K=$K_{\min}$.
2) If the ML distance ratio, γ is larger than γ_{low} but less than γ_{high} : channel environment is bad, inaccurate estimates from ZF detection $\Rightarrow$ set K=K_{mid}.
3) If the ML distance ratio, γ is less than γ_{low} : channel environment is the worst unreliable estimates from ZF detection $\Rightarrow$ set K=$K_{\max}$.

We set the threshold parameters, $\gamma_{low}=2$ and $\gamma_{high}=7$ based on the observation made in fig. 4. By using this criterion, the proposed adaptive *K*-best algorithm can reduce the metric computation complexity while achieving almost the same performance as the system with large *K*.

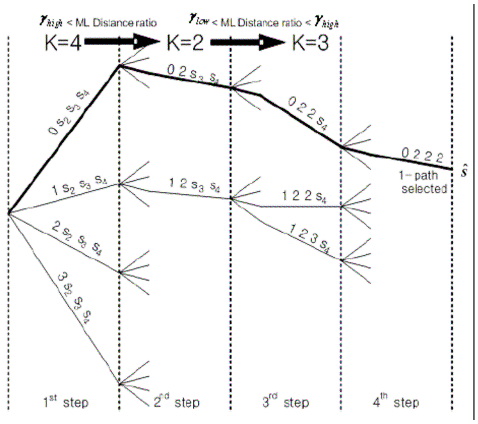

Fig. 6 Example of a search tree with adaptive ZF *K*-best scheme (with QPSK).

Ⅴ. Simulation Results

In this section, we illustrate simulation results for the proposed adaptive *K*-best algorithm for *N*=*L*=3, *N*=*L*=4 antennas with 16QAM modulation respectively. Rayleigh fading model is assumed for all propagation paths. The SER performance versus *Eb/No* with *N*=*L*=3 is shown in fig. 7. For SER=10^{-3}, the proposed algorithm with ($K_{\min}$, K_{mid},

K_{max})=(1, 16, 32) achieves about 2dB improvement over the conventional fixed *K*-best algorithm with *K*=16 while maintaining less than 12% metric computation at *Eb/No*=20dB (see Table 1). The proposed algorithm also achieves about 2dB improvement over the conventional variable *K*-best algorithm in [8] with *X*=1800, *K*=1~32 while maintaining less than 14% metric computation at *Eb/No*=20dB. Compared to the MLD algorithm, the performance degradation of the proposed algorithm with (K_{min}, K_{mid}, K_{max})=(1, 16, 32) is still rather significant, however only 3.5% metric computations are required at *Eb/No*=15dB (see Table 1).

The SER performance versus *Eb/No* with *N*=*L*=4 is shown in fig. 8. For SER=10^{-3}, the proposed algorithm with (K_{min}, K_{mid}, K_{max}) = (1, 16, 32) achieves about 3.2dB improvement over the conventional fixed *K*-best algorithm with *K* = 16 while maintaining less then 12% metric computation *Eb/No*=20dB (see Table 1). The proposed algorithm also achieves about 2.5dB improvement over the conventional variable *K*-best algorithm in [8] with *X*=1800, *K*=1~32 while maintaining less than 14% metric computation at *Eb/No*=20dB. Compared to the MLD algorithm, the performance degradation of the proposed algorithm with (K_{min}, K_{mid}, K_{max}) = (1, 16, 32) is still rather significant. However, only 0.4% metric computations are required at *Eb/No*=15dB (see Table 1).

Table 1. The number of metric computations versus Tx antennas and modulation level with MLD, ZF/*K*-best and Proposed adaptive *K*-best scheme

N	*Eb/No* (dB)	Number of metric computations				
		Proposed	Conventional Variable ZF/K-best *X*=1800	Conventional ZF/K-best		MLD
		K∈(1,16,32)	*K*∈(1~16)	*K*=4	*K*=16	
3	15	145	518	114	528	4096
	20	62	445			
	25	50	304			
4	15	262	776	208	784	65536
	20	94	701			
	25	71	541			

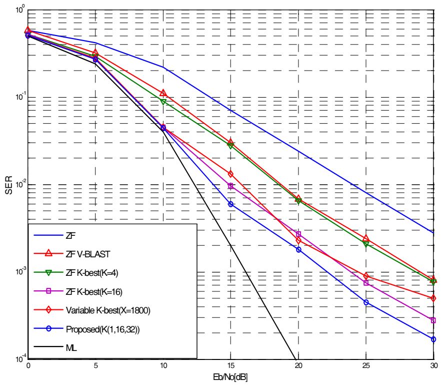

Fig. 7 SER versus Eb/No per Rx antenna for *N*=*L*=3 with 16QAM

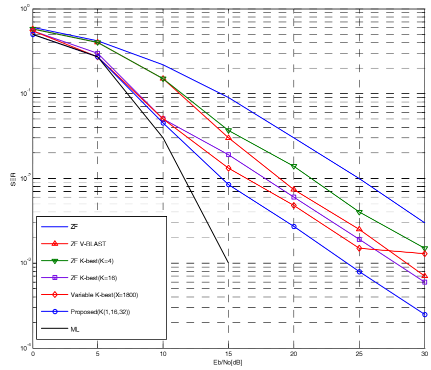

Fig. 8 SER versus Eb/No per Rx antenna for *N*=*L*=4 with 16QAM

The number of metric computation of each detection scheme is shown in Table 1. The proposed adaptive *K*-best scheme is simulated with Q=16 and *N*=*L*=3, *N*=*L*=4 antennas respectively along with the results of the conventional ZF *K*-best and the MLD. The proposed algorithm achieves about 88% metric computation reduction from the conventional ZF/*K*-best algorithm with *K*=16 and achieves about 86% metric computation reduction from the conventional variable *K*-best algorithm with *X*=1800, *K*=1~32 at *Eb/No*=20dB. Furthermore, in high SNR (*Eb/No* =20dB, 25dB), the proposed scheme achieves more than 50% computation reduction even compared to the case of *K*=4. The occurrence probability of each *K* in the proposed adaptive scheme is given in Table 2. At each *Eb/No*, *K*=1 is dominant over *K*=16 or 32. This means that just a single survivor path is enough to trace the correct path for most case and thus, the proposed algorithm can significantly reduce metric computation, while achieving almost the same performance as the system with large *K*.

Table 2. The occurrence probability of each *K* with *N*=*L*=3, and 16QAM

E_b/N_o (dB)	15	20	25
Pr[*K*=1]	84.94%	96.22%	98.96%
Pr[*K*=16]	6.4%	2.07%	0.66%
Pr[*K*=32]	8.64%	1.69%	0.46%

Ⅵ. Conclusions

We proposed an adaptive *K*-best detection scheme for MIMO systems based on the ZF and *K*-best algorithm. After ordering each component of ZF output estimates following the order of the norm of pseudo inverse, the proposed scheme changes the number of candidate according to the ML distance ratio at each *K*-best step. It is observed that the proposed algorithm offers significant reduction of computational complexity compared with the conventional ZF *K*-best algorithm and variable *K*-best algorithm while maintaining the improved SER performance.

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