An Improved K-Best Detector for MIMO WLAN Systems

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***Abstract*—The maximum likelihood (ML) detection is the optimal detection method for multiple-input multiple-output (MIMO) communication systems. The normal K-best Sphere Decoding Algorithm (SDA) can guarantee a fixed throughput, but it induces a large bit error rate (BER) degradation. In order to achieve close-to-ML performance, the *K* value needs to be sufficiently large. Thus, it needs large computation with long latency and low throughput. In this paper, an improved K-best SDA is proposed by using fixed *K* values for different layers of K-best detection, which can increase the MIMO detection performance. The architecture of 4×4 MIMO detector is designed for both 16QAM and 64QAM modulation.**

I. INTRODUCTION

Multiple-input multiple-output (MIMO) systems have interested considerable research attentions in the wireless communication field. Recently, there have been many studies on practical techniques to realize the high channel capacity in MIMO systems. It has been shown in [1] that high data rate wireless communication near *Gb/s* can be achieved in wireless local area networks (WLANs). The main challenge of the receiver design for MIMO systems lies in the detection of disorderly constellation. The MIMO techniques can basically be classified into space time coding (STC) and space division multiplexing (SDM) groups. STC increases the channel capacity of the wireless communication system by coding over different transmitter channels [2], whereas SDM employs multiple transmit and receive antennas and simultaneously transmits parallel data streams over all available spatial channels [3]. Especially, the high throughput technology has been discussed in SDM systems.

The SDM technology can be classified into linear and nonlinear detection methods [4]. Linear detection methods invert the channel matrix using a zero-forcing (ZF) or minimum mean squared error (MMSE) criterion. The drawback is, in general, a rather poor bit-error-rate (BER) performance. The vertical Bell Laboratories layered space-time (V-BLAST) algorithm is one of the nonlinear detection, which uses ordered successive interference cancellation decoders to improve the performances. Maximum likelihood (ML) algorithm is another nonlinear detection scheme and minimizes the BER. However, using optimal ML detection, the operational complexity is much higher, when we adopt higher modulation constellations and antenna numbers. Therefore, the sphere decoder (SD) algorithm has been introduced in [5], [6] to drastically reduce the operational complexity for MIMO detection. The SD algorithms have other kinds of implementation strategies, i.e., K-best SD [7] and K-best Schnorr-Euchner (SE) [8], [9].

In this paper, we propose a novel way to determine *K* value at each detected layer which is useful to improve normal K-best detector performance. We design pipelined VLSI architecture of our improved 4×4 MIMO detector for different modulation with much less computational complexity. Our proposed work can overcome the control path which is different from normal K-best detector.

This paper is organized as follows. Section II describes the MIMO detection including system model and improved detection method. Architecture design results for K-best detector are given in Section III. Section IV shows simulation results, and Section V concludes the paper.

II. MIMO DETECTION

A. MIMO System Model

To increase the data rate of the wireless communication, the spatial multiplex is used in the MIMO system with *Nt* transmitted antennas and *Nr* received antennas. The baseband equivalent model can be described in Eq. (1).

$$\mathbf{Y}=\mathbf{HS}+\mathbf{n} \tag{1}$$

At each symbol time, a vector $\mathbf{S} = [s_1, s_2, .., s_{Nt}]^T$ with each symbol belonging to the *q* quadrature amplitude modulation (*q*-QAM) constellation passes through the channel response $Nr \times Nt$ matrix **H**. The received vector $\mathbf{Y} = [y_1, y_2, .., y_{Nr}]^T$ at the receiving antenna for each symbol time is a noisy superimposition of the *Nt* signals contaminated by additive white Gaussian noise (AWGN).

The complex matrix Eq. (1) can be transformed to its real matrix representation as Eq. (2).

$$\begin{bmatrix} \Re(Y) \\ \Im(Y) \end{bmatrix} = \begin{bmatrix} \Re(H) & -\Im(H) \\ \Im(H) & \Re(H) \end{bmatrix} \begin{bmatrix} \Re(S) \\ \Im(S) \end{bmatrix} + \begin{bmatrix} \Re(n) \\ \Im(n) \end{bmatrix} \tag{2}$$

B. The pre-processor with QR-Decomposition

We concentrate ourselves on the symmetric case, i.e., $Nr=Nt$ and use QR-decomposition of **H**. With **H=QR,** Eq. (1) can be rewritten as Eq. (3).

$$\begin{aligned}\hat{\mathbf{y}} &= \mathbf{Q}^H\mathbf{Y} = \mathbf{Q}^H(\mathbf{HS}+\mathbf{n}) \\ &= \mathbf{Q}^H(\mathbf{QRS}+\mathbf{n}) = \mathbf{RS}+\mathbf{Q}^H\mathbf{n}\end{aligned} \tag{3}$$

where **R** is upper triangular matrix and **Q** is unitary matrix.

C. K-Best Sphere Decoding Algorithm

The ML detector is the optimum detection algorithm for the MIMO system. It requires finding the signal point **S** from all transmit vector signal set that minimizes the Euclidean distance with respect to the received signal vector **y** with QR-decompositions as qiven in Eq. (4) ：

$$\hat{s} = \arg min\|\mathbf{Y}\text{-}HS\|^2 = \arg min\|\hat{\mathbf{y}}\text{-}RS\|^2 \tag{4}$$

Expanding the vector norm in Eq. (4) yields into Eq. (5) ：

$$\hat{s} = \arg min\sum_{i=1}^{Nt}\left\|\hat{y}_i - R_{ii}S_i - \sum_{j=i+1}^{Nt}R_{ij}S_j\right\|^2 \tag{5}$$

The detection process starts from the last layers $l=Nt$ and works the way until the first layer is detected. It is to perform an exhaustive search of all possible combinations of the transmitted symbols that minimizes $\|\mathbf{Y\text{-}HS}\|^2$.

The branch cost function associated with nodes in the i-th layer is：

$$T_i(s^i) = T_{(i+1)}(s^{(i+1)}) + |e_i(s^i)|^2$$

$$\text{with} \quad e_i(s^i) = \hat{y}_i - R_{ii}S_i - \sum_{j=i+1}^{Nt}R_{ij}S_i \tag{6}$$

Each node in the tree corresponds to a so-called *partial Euclidean distance* （PED）$T_i(s^{(i)})$,where $T_{Nt+1}(s^{(Nt+1)}) = 0$ and term $|e_i(s^{(i)})|^2$ denotes the distance increment between two successive nodes in the tree.

At each layer, K-best detector approximates a breadth-first search by keeping only K candidates with the smallest PEDs are kept for the next level search.

In [5] a simplified norm algorithm was first introduced. The l^2-norm was replaced using different norms to reduce complexity and increase the efficiency of the tree pruning. In [4], the l^2-norm is compared with the l^1-norm and the l^∞-norm on circuit complexity. Both of the l^1-norm and the l^∞-norm has shorter delay and less area than the l^2-norm.Thus we adopt the l^1-norm in our design. By setting $T_i=X_i^2$ and using the corresponding approximation, Eq. (7) can be rewritten as

$$\begin{aligned}&X_i(S^{(i)}) \approx |X_{i+1}(S^{(i+1)})| + |e_i(S^{(i)})| \\ &|e_i(S^{(i)})| \approx |\Re\{e_i(S^{(i)})\}| + |\Im\{e_i(S^{(i)})\}|\end{aligned} \tag{7}$$

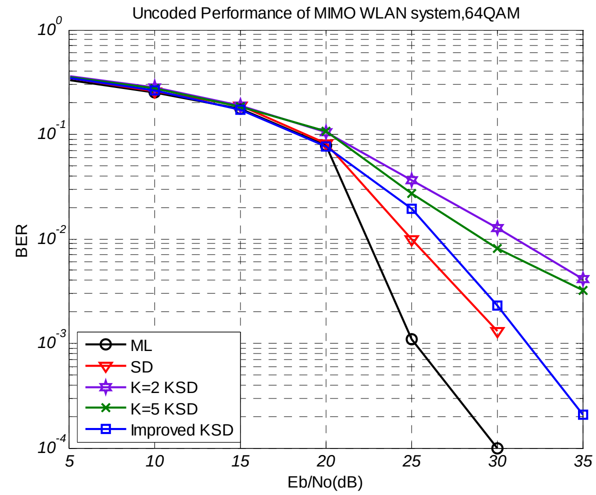

Figure 1. Performance Comparisons of ML,SDA,2-Best SDA, 5-Best SDA, Impoved KSDA（$Nr=Nt=4$, 64QAM）

D. Improved K-Best SDA

Figure 1 shows the simulation results, which compare the performance of MLD, SDA, normal 2-best SDA, normal 5-best SDA at different signal to noise ratio (SNR). We can see the BER performance of the normal 5-best SDA worse than the SDA and MLD. Based on the simulation results, when K is very small, the performance significantly decreases. For example, K=2 in the figure. Thus, how to choose appropriate K value is very important.

In [9], a dynamic K-best SDA method was introduced. However, such dynamic K-best SDA does not have regularity to adapt K value in each detected layer.

We proposed a fixed way that has regularity to select the K value at different detection layers for different modulations as given in Eq. (8) ：

$$k_N = int\left[\frac{\alpha \times Rc \times L \times N}{\sqrt{Eb/No}}\right], \; N \in \{N_r, N_r - 1, N_r - 2, ..., 1\} \tag{8}$$

where L is the number of bits per symbol, Rc is the code rate, N is the current detection layer, α is adjusted to control the K value constraint flexibly and adaptively and *int* here means that we just round it to the nearest tens.

The α value is assumed by considering the effect of our work performance and hardware design complexity. The number of node search decreases from detected layer Nr to layer 1. Increasing K value at early stages can reduce the possibility of missing the possible ML solution, and the performance is increased. In the system with a low SNR we will have a larger K value, since it is beneficial to reduce missing possible candidates.

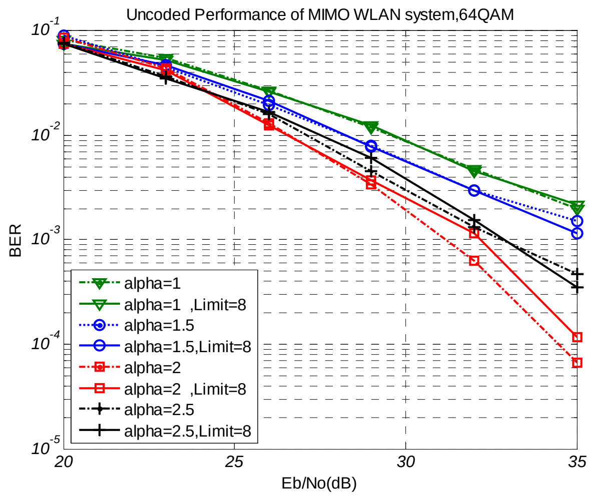

Figure 2. The uncoded BER simulation with different α values form 1 to 2.5 of MIMO system（*Nr*=*Nt*=4 , 64QAM）

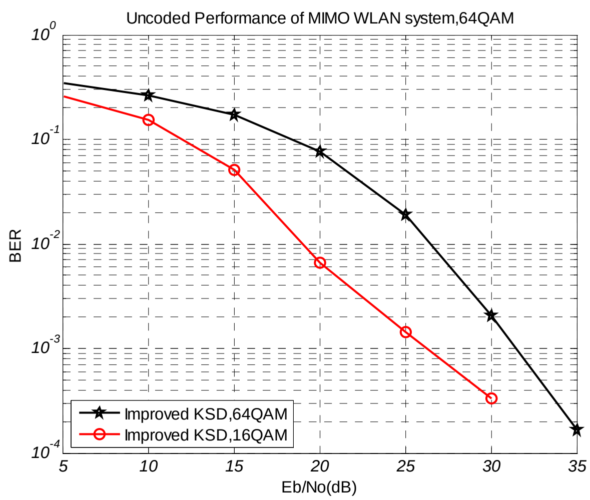

Figure 3. Simulation result of proposed K-best algorithm with 16QAM and 64QAM modulation in uncoded MIMO system（*Nr*=*Nt*=4）

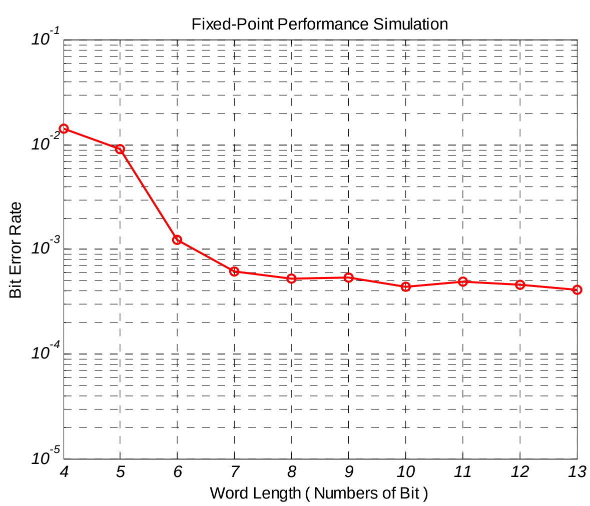

Figure 4. Word length simulation result of proposed K-best algorithm in uncoded MIMO system（*Nr*=*Nt*=4 , 64QAM）

III. SIMULATION RESULTS

One analysis of different α values is shown in Fig. 2, while we adopt α value from 1 to 2.5 with and without limit. According to this analysis, α=2 can be adopted to obtain better performance when we use the proposed K-best algorithm to detect 4×4 MIMO system. The limit parameter is to limit the K-best number at eight for decreasing hardware complexity.

Fig. 3 compares 16QAM with 64QAM while using the proposed K-best algorithm at the receiver of MIMO systems. For comparison, this figure also shows the performance over the AWGN with multi-antennas Nr=Nt=4 and without channel coding. Figure 3 clearly indicates that the 16QAM can outperform the 64QAM in MIMO detection.

The fixed-point number is a finite word-length representation of the corresponding floating-point number. The fixed-point number is in two's complement format which includes one sign bit, four integer bits, and the fractional bits. Fig. 4 shows the analysis of the fractional word-lengths for hardware design. If the fractional word-length is longer than 7 bits, then the BER is saturated with a SNR of 32 dB. Therefore, fractional word-lengths of 9 bits should be chosen for hardware implementation.

IV. ARCHITECTURE

The proposed architecture of the K-best detector is designed to reduce the computation complexity, which is a useful attribute for 16QAM and 64QAM modulation. The flowchart of the proposed detector is shown in Figure 5. To start with the channel estimation, we can get current channel information **H**. Then the received vector **Y** was preprocessed by QR decomposition to get the vector $\hat{y}$ and the signal **R**, which is the element of the upper triangular matrix of channel preprocessing. At the same time, we use **H** to estimate current SNR value and apply it to calculate K for each detected layer. The shaded portion is the main K-best detector module, which has Nr pipelined stage. For each stage, there are two sub modules：PED Computation Unit and Sorting Unit. The ***i***-th stage receives K smallest PEDs (T_i) from the preceding stage and expands each parent nodes to all their children nodes. Then data vectors $\boldsymbol{S_i}$ consist of admissible nodes. Finally, we can determine the detected vector $\hat{S}$.

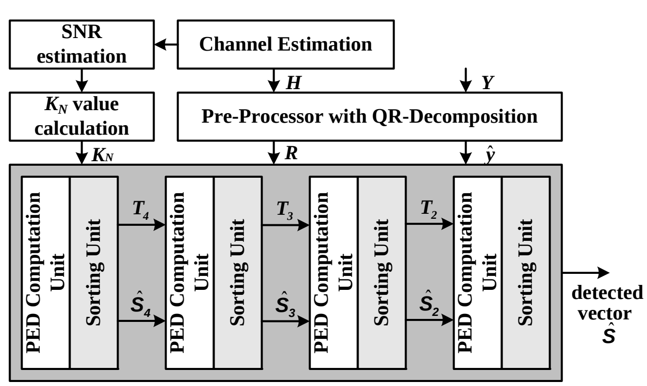

Figure 5. The flowchart of proposed K-best detector

From the block diagram in Fig. 5, the main operation blocks of PED computation unit and sorting unit are clearly described. Figure 6 shows the architecture of PED computation unit, which includes constellation multipliers for 16QAM or 64QAM, adders, and l^1-norm operations. The PED block computes the PEDs of all associated children of the parent node. The different QAM computing can be changed by the QAM select control line to achieve hardware flexibility.

The role of the sorting unit in this architecture is to sort all the generated PEDs and select the smallest K PEDs. The most challenging aspect of the design of a sorting unit is to reduce the number of operation times in the architecture. The dataflow graph of a functional unit for the machine is shown in Fig. 7. The sorting method adopts a bubble scheme operation as shown in Fig.7-(a). The bubble scheme architecture approaches the latency at $\sum_{j=1}^{K}(N-j)$, where N denotes the constellation of the PEDs output and K is the number of K-best. The dataflow graph has feedback, because the contents of a memory cell can be written back to the cell as shown in Fig. 7-(b).

V. Conclusion

In the detection of MIMO systems, a K-best sphere decoding is designed for the receiver, which can improve the MIMO detection performance. This paper proposes a MIMO detector hardware structure and analyzes the word-length required to obtain sufficient performance for hardware implementation. Simulation results indicate that the proposed K-best rule is better than that of other existing normal K-best algorithm.

Acknowledgments

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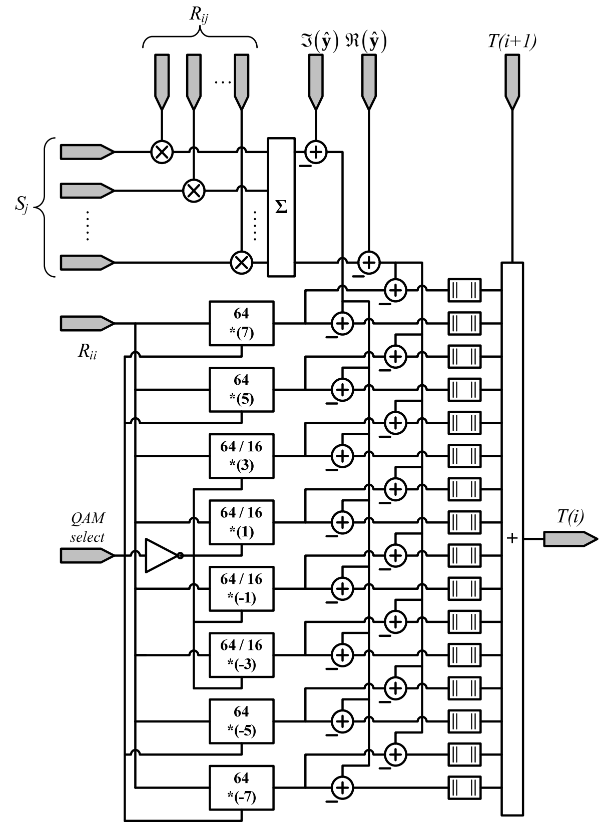

Figure 6. Architecture of PED Computation Unit

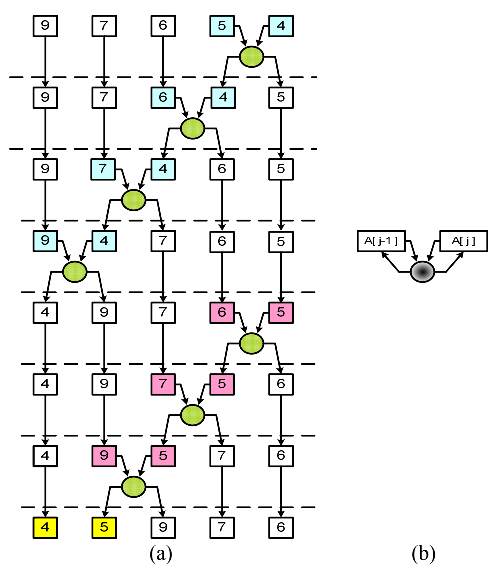

Figure 7. Architecture of Sorting Unit : (a) Data flow graph , and (b)baseline functional unit