VOL. 10, NO. 5, MARCH 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

MODIFIED K-BEST DETECTION ALGORITHM FOR MIMO SYSTEMS

Shirly Edward A. and Malarvizhi S.
Department of Electronics and Communication Engineering, SRM University, Vadapalani, Chennai, India
E-Mail: edward.s@vdp.srmuniv.ac.in

ABSTRACT

This paper presents a VLSI implementation of reduced hardware-complexity and reconfigurable signal detector for MIMO (Multiple-Input Multiple-Output) systems. In recent wireless communication system, MIMO technique is being adopted to meet the rapidly increasing demands for the multimedia services and to achieve better QoS(Quality of Service). Maximum likelihood (ML) detection is the optimal hard decision detection for MIMO systems. FPGA implementation of ML detector becomes infeasible as its complexity grows exponentially with the number of antennas. Therefore, we propose a modified K-best detector algorithm which employs parallel and distributed sorting strategy that has a constant throughput and near-ML detection solution. The proposed MIMO detector was implemented targeting Xilinx Virtex 6 device for a 2x2, 4 QAM system and it achieves throughput of 12.23Mbps. The resource utilization results are listed and compared with the existing algorithm. The total on-chip power estimated is 1.57W.

Keywords: MIMO (multiple-input multiple-output), maximum-likelihood (ML), sphere decoder, K-best algorithm, very large scale integration (VLSI).

1. INTRODUCTION

Multiple-input multiple-output (MIMO) system is one of the wireless communication technologies which provide increased data throughput and link range without additional bandwidth and transmit power [1]. MIMO plays a key role in every new wireless standard, such as HSDPA, 802.11n, 802.16e and 3GPP-LTE. The main challenge in exploiting the potentials of MIMO technology is the requirement of high computing power at the receiver end.

MIMO systems can be employed to improve the transmission quality by diversity and spatial multiplexing methods, but separation of multiplexed streams of data is the main implementation challenge in terms of computational complexity and power consumption. Therefore an efficient VLSI implementation is the key to enable low power, high performance and low cost equipment. The maximum –likelihood (ML) detectors using exhaustive search gives the optimal solution. To reduce the exponential complexity in ML decoders, sphere decoders [2] are proposed to achieve near-ML performance and reasonable complexity. QR decomposition technique is used to reduce the complexity by the process of tree search and pruning. Algorithms like depth-first search, breadth –first search, fixed complexity technique and best first search are available for pruning the tree.

In [3], Burg first implemented the hard output depth-first search algorithm and Guo implemented the soft –output K-best decoder [4].The parallel merge algorithm was proposed in [5] to increase the throughput of the conventional K-best architectures. Some researchers divide the whole search tree into several parts [6, 7] and implement K-best algorithm but the complexity does not decrease further.

In this paper, we present the FPGA implementation of a sphere detector using modified K-best algorithm that supports 4-QAM with a combination of 2 antennas. The breadth-first search is modified to decrease the latency and hardware complexity of the algorithm. A parallel and distributed sorting strategy is employed to exploit the parallelism of the FPGA in order to achieve high data rates.

In Section II and III of this paper MIMO system model, Maximum Likelihood detection and K-best algorithm for sphere detection are discussed in brief. The real value decomposition technique and the tree formation are briefly presented in Section IV. Section V and VI presents the modified K-best algorithm and its VLSI architecture. In Section VII the implementation and results are discussed. Section VIII concludes the paper.

2. MIMO SYSTEM MODEL

Consider a MIMO system with N_T transmit and N_R receive antennas. The equivalent complex-valued discrete –time baseband model of the MIMO channel between the transmitter and receiver is described by an N_T x N_R dimensional matrix H. The N_R –dimensional received signal vector is given by

$$y = Hs + n \tag{1}$$

Where $s = [s_1 s_2 .... s_{N_T}]^T$ the N_T –dimensional transmit signal vector and n stands for the N_R –dimensional additive i.i.d circularly symmetric complex Gaussian noise vector with variance N_o per complex-valued dimension. The entries of s are chosen independently from a set O of complex-valued constellation points with Q bits per scalar symbol, i.e., $|O| = 2^Q$. The set of all possible transmitted vector symbols is denoted by O^{N_T}.

The Maximum Likelihood (ML) criterion for estimating s from y, assuming perfect knowledge of the channel matrix H, is given by

$$\hat{s} = \arg\min_{s \in O^{N_T}} \|y - Hs\|^2 \quad (2)$$

The ML solution can be obtained through an exhaustive search in a MIMO system. However, it is impractical to perform an exhaustive search for a large MIMO system. Therefore, Sphere Decoding (SD) algorithms are proposed to reduce the computational complexity by converting into a tree search problem. An efficient pruning criteria is used to decrease the number of visited nodes. SD takes into account only the lattice points that are inside a sphere of a given radius r. The following inequality is referred to as the sphere constraint:

$$\| y - Hs \|^2 < C \quad (3)$$

Where C is the squared radius of the sphere and y is the center of the sphere.
The channel matrix H can be decomposed by QR decomposition, and then equation (3) can be written as

$$\| y' - Rx \|^2 \leq C' \quad (4)$$

Where $C' = C - \| (Q')^H y \|^2$ and $y' = Q^H y$ .R is an upper triangular matrix with positive diagonal elements and Q is a matrix with orthogonal columns.

The basic idea behind tree-search algorithms lies in the transformation of the ML detection problem into a tree search problem. In tree search algorithm the distance between the received vector y and the candidate received vector symbols Hs can be decomposed into partial Euclidean distances d_i which depend only on s. The symbol s increases strictly when proceeding from a parent node to one of its children. The algorithm finds the leaf that is associated with the smallest d_i which corresponds to the ML solution.

3. K-BEST ALGORITHM

Based on the search strategy, the sphere detector algorithm can be divided into depth-first and breadth–first method. The K-best algorithm [4] follows a breadth-first search technique which does not require a sphere constraint. Tree pruning is enabled by constraining the cardinality of the set of admissible nodes on each level of the tree to a parameter K. The breadth–first algorithm searches for the PEDs in the forward direction only and the best K candidates based on PEDs are kept at each level in the tree. The candidates are selected from the set by giving precedence to those children which yield the smallest associated PEDs.

The main advantage of the K-best breadth first search algorithm over depth-first algorithm is its fixed complexity, which is determined by the parameter K. The choice of parameter K also entails a trade-off between the complexity and BER performance. If K is chosen to be very large, complexity and memory requirements are high. But if K is small, there is a chance of accidentally excluding the ML solution from the list of candidate vector symbols. The value of K should be kept as large as possible without compromising on the optimality, compared with ML algorithm. Limiting the value of K can reduce the complexity of the breadth-first search algorithm.

4. REAL-VALUED DECOMPOSITION

The received signals in the receiver are in the complex domain as shown in Equation (1). The sphere decoding algorithm discussed can be applied only when the real and imaginary components of y, H and s are decoupled, to form a real system with equations which will $s \in O^{N_T}$ have twice the dimension of the complex system [8]. Therefore, the received N_T dimensional complex-valued system model is decomposed into an equivalent $2N_T$ dimensional real-valued system model according to the following equation.

$$\begin{bmatrix} R(y) \\ I(y) \end{bmatrix} = \begin{bmatrix} R(H) & -I(H) \\ I(H) & R(H) \end{bmatrix} \begin{bmatrix} R(s) \\ I(s) \end{bmatrix} + \begin{bmatrix} R(n) \\ I(n) \end{bmatrix} \quad (5)$$

The real-valued decomposition transforms the original search tree into a tree with twice the depth.

From the Table-1 it is clear that when operating directly on complex constellation points, $K|O|$ PEDs must be calculated in each step whereas applying RVD reduces the number to only $K\sqrt{|O|}$ PEDs. Therefore, the overall silicon complexity of the individual processing element is much lower with RVD.

Table-1. Comparison of real-valued and complex-valued systems.

MIMO system configuration	Real-valued system		Complex-valued system	
	Depth	No. of sub nodes	Depth	No. of sub nodes
2x2 ,4 QAM	4	2	2	4
2x2,16 QAM	4	4	2	16
4x4,16 QAM	8	4	4	16

Figure-1 shows the decision tree structure for 4-QAM, 2x2 MIMO System. After real value decomposition the tree has four layers. The metric values of Eq. (2) can be calculated sequentially following the decision tree structure. At each node in the tree a decision has to be made for either a sent +1 or a sent -1 , such that the uppermost path through the tree corresponds to a sent sequence(+1,+1,+1,+1).

VOL. 10, NO. 5, MARCH 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

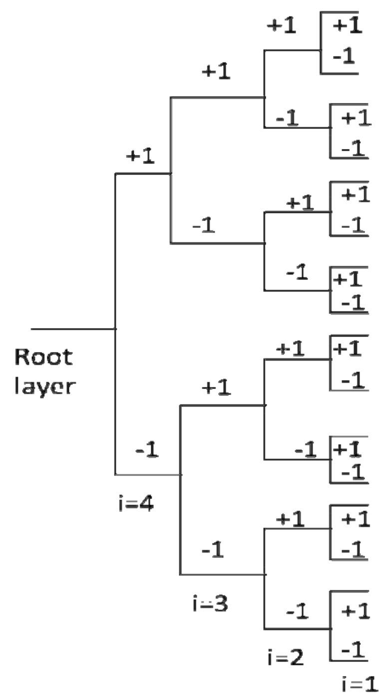

Figure-1. Decision Tree structure for 4-QAM 2x2 MIMO system.

5. MODIFIED K-BEST ALGORITHM

The breadth-first algorithm can be modified in order to decrease the latency, by calculating two PEDs in parallel and discarding the larger one. In our design, the processing element computes PEDs of all children of a single parent node in one cycle.

We employ parallel and distributed sorting strategy [9] in our algorithm. The steps are given as:

1. Distribute the parent nodes into two different sets.
2. Parallel comparison for these set of nodes are done using comparators and best node selected.
3. The path extension is done based on best children nodes.

The algorithm is summarized as follows:

Input :y, H, M_T=2N_T,H=QR

Algorithm:

1. Initialize d_{i+1} = 0 and i=M_T
2. Calculate the PEDs for the symbol set at level I using the equation.

$$d_i = d_{i+1} + \left\| y_i - \sum_{j=i}^{M_T-1} r_{i,j} s_j \right\|^2$$

3. While(i>0) do
4. if (i=M_T) then
5. {Calculate d_i for K symbols s_j.
6. Set s_j as parent node and continue}
7. else
8. {calculate d_i for all leaf nodes of s_j
9. compare and select the best PED for each s_j
10. expand the tree with the nodes of K best PEDs}
11. end if
12. end while

In the last layer, the PEDs obtained are sorted and the best one and its symbol set are given as output. This output represents the hard decision output of the decoder. The parallel implementation allows the algorithm to give a fixed throughput.

6. VLSI ARCHITECTURE

The block diagram for the K-best sphere decoder is shown in Figure-2. The blocks were divided into separate units and processing can therefore be implemented in a parallel fashion.

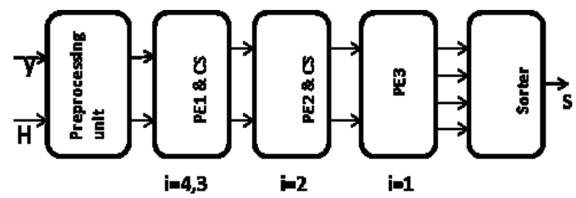

Figure-2. Block diagram of the modified K-best algorithm.

In the preprocessing unit, the inputs y and H are buffered, QR decomposition done and received vector y is multiplied with Q^H. The input vector and the channel matrix dimension are doubled by real value decomposition. The PE1and CS unit calculates the Partial Euclidean Distances with $d_4 = \left\| y_4 - R_{4,4} s_4 \right\|^2$, where s_4 is the set of possible partial transmitted symbols. For layer i=3, PEDs are computed by $d_3 = \left\| y_3 - R_{3,3} s_3 - R_{3,4} s_4 \right\|^2$ and the PED from the previous list is added to the result corresponding s_4. The PEDs of the leaf node of respective s_4 are compared and the smallest PED and its symbol set are fed as input to the next PE2 unit. In PE2 and CS unit, the computation of $d_2 = \left\| y_2 - R_{2,2} s_2 - R_{2,3} s_3 - R_{2,4} s_4 \right\|^2$ and the smallest PEDs from the previous layer is added to the result corresponding $s_4 s_3$. The PEDs of the leaf node of respective $s_4 s_3$ are compared in parallel and the smallest PEDs and its symbol sets are fed to PE3 unit. The PE3 unit computes $d_1 = \left\| y_1 - R_{1,1} s_1 - R_{1,2} s_2 - R_{1,3} s_3 - R_{1,4} s_4 \right\|^2$ and the smallest PEDs from the previous layer is added to the result corresponding $s_4 s_3 s_2$. The PEDs of the leaf node of respective $s_4 s_3 s_2$ are compared in parallel and the smallest PEDs and its symbol sets are given as output. The output PEDs are sorted and the symbol set which has the smallest PED is the optimal estimate of the received symbol.

7. IMPLEMENTATION AND RESULTS

The modified K-best algorithm has been implemented using Xilinx Plan Ahead Design tool [10]. In Plan a head software, the implementation and timing results can be viewed to analyze the critical logic and to improve the design performance with floor planning and constraint modification. The Xilinx Plan Ahead Design tool is used to implement and verify the proposed algorithm and its VLSI architecture on the Xilinx Virtex 6 FPGA for 8-bits precision with $N_T = 2$.

We had considered a 2x2 MIMO system with 4-QAM modulation for our design. At the receiver, the channel information is assumed to be known perfectly. The Rayleigh fading channel is taken into consideration. The estimated complex channel matrix H is converted into real valued matrix through RVD, in order to reduce the complexity of the algorithm. The hardware resources were estimated for the architecture and compared with the results obtained in [11] and presented in Table-2. From the comparison it can be inferred that our proposed design requires less number of slice logic utilization. The PE1 and CS block takes 19 clock cycles for PED calculation and sorting for layer 4 and 3. In layer2, the PE2 and CS unit takes 25 clock cycles and 31 clock cycles for layer1 as given in Table-3. From the timing analysis, it is found that the minimum time period taken for the design is 3.646ns. Therefore, the maximum achievable clock frequency is found to be 274.273MHz. The power estimation of the algorithm mapped on a FPGA device can be found using Xpower Analyzer Tool. The total on-chip power of the design is 1.57W.

Table-2. Comparison between K-Best SD implementation.

Parameters	Our proposed work	[11]
Antenna system	2x2	2x2
Modulation	4QAM	4QAM
Algorithm	K-best algorithm	K-best algorithm
Technology	Xilinx Virtex 6	Xilinx Virtex 4
Slices	526	913
DSP48E1s	58	28

The maximum throughput of the detector with reference to [12] is calculated by the Eq.(6)

$$\text{Throughput} = \frac{f_c \cdot \log_2(M) \cdot N_T}{C} \quad (6)$$

Where f_c is the maximum clock frequency, M is the constellation size, N_T is the antenna number and C is the number of clock cycles needed for calculating the PEDs in one layer. For our detector design, the parameter C = 27. Therefore, the maximum throughput achieved for the design would be 12.23Mb/s.

Table-3. Latency comparison.

Blocks	PED Calculation (# of clock cycles)	Sorting (# of clock cycles)
PE1&CS	15	4
PE2&CS	21	4
PE3& CS	27	4

8. CONCLUSIONS

In this paper, we presented a reconfigurable VLSI architecture for the proposed modified K-best algorithm. The architecture of a 2x2 MIMO antenna system sphere decoder for 4-QAM and implementation results were discussed. The proposed design utilizes parallel and distributed sorting which requires less number of comparators. The hardware complexity reduces to a greater extent which is evident from the resource utilization results, but still with near ML performance. In practice, the detector is usually attached with channel decoders to provide robustness against fading and noisy wireless channels. Our future work will be to implement the proposed architecture for higher order modulation with different antenna configurations and with further performance enhancement for emerging wireless communication standards.

REFERENCES

[1] Paulraj A. V. Gore D.A. and Nabar R. U. 2004. An overview of MIMO communications a key to gigabit wireless. Proceedings of the IEEE, Vol.92, No.2, pp. 198–218.

[2] B. Hassibi. and H. Vikalo. 2001. On the expected complexity of sphere decoding. In: Proceedings of thirty fifth Asilomar Conference on Signals, Systems and Computers. pp. 1051–1055.

[3] A. Burg, M. Borgmann, M. Wenk, M. Zellweger, W. Fitchner. and H. Bolcskei. 2005. VLSI implementation of MIMO detection using sphere decoding algorithm. IEEE Journal of Solid-State Circuits. Vol. 40, no.7, pp.1566-1577, July.

[4] Z. Guo. and P. Nilsson. 2006. Algorithm and implementation of the K-best sphere decoding for MIMO detection. IEEE Journal on Selected Areas in Communications. Vol.24, no.3, pp.491-503, March.

[5] N. Moezzi-Madani. and W. Davis. 2009. Parallel merge algorithm for high-throughput signal

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

processing applications. Electronics Letters. Vol. 45, pp.188.

[6] P. Radosavljevic, K. J. Kim. and H. Shen. e*t al*. 2012. Parallel searching-based sphere detector for MIMO downlink OFDM systems. IEEE Transactions on Signal Processing. Vol.60, no.6, pp.3240-3252.

[7] C. A. Shen. and A. M. Eltawil. 2010. A radius adaptive K-best decoder with early termination. IEEE Transactions on circuits and Systems I.Vol.57, no.9, pp.2476-2486.

[8] Bertrand M. Hochwald. and Stephan Ten Brink. 2003. Achieving Near-Capacity on a Multiple-Antenna channel. IEEE Transactions on Communications. Vol.51, No.3, pp.389-399.

[9] B. Kim. and Park.I-C. 2008. K-best MIMO detection based on interleaving of distributed sorting. Electronics Letters. Vol.44, No.1.

[10] Xilinx Plan Ahead Design Tool, Reference Guide: http//:www.Xilinx.com

[11] Johanna Ketonen, Markku Juntti. and Joseph R. Cavallaro. 2010. Performance –complexity comparison of Receivers for a LTE MIMO-OFDM System. IEEE Transactions on Signal Processing, Vol.58, No.6, pp. 3360-3372.

[12] Liang Liu, Johan Lofgren. and Peter Nilsson. 2012. Area-Efficient configurable High-throughput signal detector supporting Multiple MIMO modes. IEEE Transactions on circuits and systems- I: Regular Papers. Vol. 59, no.9, pp. 2085-2096.