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Design and FPGA-Implementation of Minimum PED Based K-Best Algorithm in MIMO Detector

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Abstract

Minimum Partial Euclidean Distance (MPED) based K-best algorithm is proposed to detect the best signal for MIMO (Multiple Input Multiple Output) detector. It is based on Breadth-first search method. The proposed algorithm is independent of the number of transmitting/receiving antennas and constellation size. It provides a high throughput and reduced Bit Error Rate (BER) with the performance close to Maximum Likelihood Detection (MLD) method. The main innovations are the nodes that are expanded and visited based on MPED algorithm and it keeps track of finally selecting the best candidates at each cycle. It allows its complexity to scale linearly with the modulation order. Using Quadrature Amplitude Modulation (QAM) the complex domain input signals are modulated and are converted into wavelet packets and these packets are transmitted using Additive White Gaussian Noise (AWGN) channel. Then from the number of received signals the best signal is detected using MPED based K-best algorithm. It provides the exact best node solution with reduced complexity. The pipelined VLSI architecture is the best suited for implementation because the expansion and sorting cores are data driven. The proposed method is implemented targeting Xilinx Virtex 5 device for a 4 × 4, 64-QAM system and it achieves throughput of 1.1 Gbps. The results of resource utilization are tabulated and compared with the existing algorithms.

Keywords

**Multiple Input Multiple Output Detector, K-Best Algorithm, Partial Euclidean Distance,
Quadrature Amplitude Modulation, Field Programmable Gate Array**

1. Introduction

Today MIMO system is one of the wireless communication technologies which provide increased data throughput and link range without any additional bandwidth. MIMO plays a key role in every new wireless standard,

such as HSDPA (High Speed Download Packet Access), IEEE 802.11n [1], IEEE 802.16e and 3GPP-LTE. At receivers, MIMO signal detection plays an important role in meeting the tough requirements of real-time processing. The design of low complexity, high performance and high throughput receivers are the key challenges in the design of any MIMO receiver. Several MIMO detection algorithms have been proposed to address this challenge, which offers various tradeoffs between the performance and the computational complexity.

Among the large variety of the MIMO detection techniques Maximum Likelihood (ML) detection [2] provides the optimum solution with minimum BER but the computational complexity of full search grows exponentially as the increase in the constellation size or the number of transmitting and receiving antennas. On the other hand, linear detection algorithms such as the Successive Interference Cancellation (SIC) detectors [2] or Minimum Mean-Square Error (MMSE) detection [3] and Zero-Forcing (ZF) can greatly reduce the computational complexity but at the same time they have reduced performance.

Finally to solve the trade-off between complexity and performance loss tree search algorithms are introduced. Depth-first and Breadth-first search algorithms are two main categories in tree search algorithms. In Depth-first search algorithm the tree is traversed in both forward and backward direction with variable throughput which results in extra overhead in hardware. But in Breadth-first search algorithm [4] the tree is traversed only in the forward direction with fixed throughput. A well-known approach in Breadth-first search method is the K-best algorithm [4]. The K-best algorithm guarantees a Signal to Noise Ratio (SNR)-independent fixed-throughput with a performance close to ML. In each cycle, K (Parent node) $\times M$ (Child node) children should be enumerated, which results in large computation complexity in K-best algorithm. Here the K values are selected randomly. To increase the value of K, the performance result becomes close to the ML detection. However, a higher K value results in more hardware complexity. Thus K = 10 is close to ML while having moderate complexity for a 4 $\times$ 4, 64-QAM MIMO system [5].

In this paper, to reduce the computational complexity in K-best algorithm, a MPED based K-best algorithm is designed and implemented on FPGA board (a reduced complexity systems), which making a significant reduction in the over-all hardware/software complexity of the system. The K value is chosen based on the square root of constellation order of QAM. So for a 4 $\times$ 4, 64-QAM MIMO detector with K = 8 is chosen. All the results presented on system performance were first tested in Matlab and then translated into hardware blocks in Simulink using Xilinx System Generator (SysGen). Once the hardware designs were completed, the bit streams were generated using Xilinx synthesis tools, which were required for the FPGA implementation. An efficient VLSI implementation is the key to enable real-time wireless communication.

2. MIMO System

Assume the MIMO system with N_t transmitting and N_r receiving antennas as shown in **Figure 1**. The equivalent baseband signal between the transmitting antenna and receiving antenna for the AWGN channel is stated in a complex-valued $N_t \times N_r$ channel matrix $\boldsymbol{H}$ [6].

The complex-valued base band received signal is expressed as,

$$\boldsymbol{Y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{e} \tag{1}$$

where $\boldsymbol{x} = \left[x_1, x_2, \cdots, x_{N_t} \right]^{\mathrm{T}}$ in which N_t-dimensional complex transmitting signal vector, from which each element is obtained independently from the complex constellation of QAM. $\boldsymbol{Y} = \left[Y_1, Y_2, \cdots, Y_{N_r} \right]^{\mathrm{T}}$ in which N_r-dimensional complex received signal vector, $\boldsymbol{e} = \left[e_1, e_2, \cdots, e_{N_r} \right]^{\mathrm{T}}$ is a complex-zero mean Gaussian noise
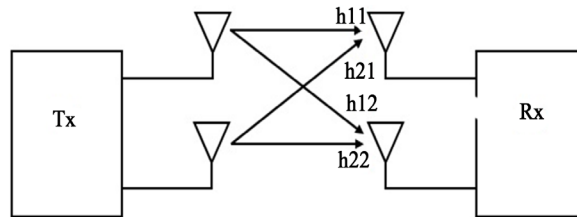

Figure 1. MIMO channel model.

with the variance of σ^2 per dimension. A complex domain frame work is developed here; and on the other hand for the received signal, the real value decomposition can also be derived [7].

Due to the intrinsic challenges in the implementation in the complex domain, most of the MIMO detection algorithms in the literature have been proposed for the real domain [5]. On account of the deeper search tree, the real domain implementation results in a larger silicon area and a larger latency. However, in the complex domain a high throughput MIMO detector with an acceptable complexity for the high-order constellations has always been a challenge in the literature. To address this challenge, a high throughput detection algorithm along for a 4×4, 64-QAM complex MIMO detector with its VLSI architecture is proposed, which is scalable to higher order constellation schemes (256-QAM) and for larger number of transmitting and receiving antennas.

K-Best Algorithm

In K-best algorithm each level of the tree is expanded from root to the leaves and selects the best candidates with the lowest path metric that is possible in each level. The path at the last level of the tree with the lowest Partial Euclidean Distance (PED) is the hard-decision [8] output of the detector, whereas, all of the existing paths at the last level of the tree are considered to calculate shortest path node is the soft-decision [8] output of the detector. The size of the tree search grows considerably when the constellation size is increased one. Therefore, at each level of the tree an enhanced way is needed to calculate the K-best candidates without performing an exhaustive search.

The objective of the MIMO detection method is to find the closest lattice points [9] for a given received signal

$$S = \arg\min_{x \in O^{N_t}} \left\| Y - Hx \right\|^2 \tag{2}$$

where O is the set of vectors from the real entries in the constellation.

The channel matrix H is QR decomposed as $H = QR$, where Q is the unitary $N_r \times N_t$ matrix and R is the upper triangular $N_t \times N_t$ matrix. By taking hermetian of Q or (Q^H), the nulling operation can be performed, which results in $Z = Q^H \times Y$, which in turn equals to $Rx + w$, where $w = Q^H + e$, the nulling matrix is always known to be one, where the noise w after nulling remains spatially white. Since R is an upper triangular matrix in nature, hence the Equation (2) can be represented as

$$S = \arg\min_{x \in O^{N_t}} \sum_{i=1}^{2N_t} \left| z_i \right| - \sum_{j=i}^{2N_t} \left| r_{ij} e_j \right|^2 \tag{3}$$

the Equation (3) is considered as an tree-search problem with N_t levels, where, starting from the last row, one symbol is detected and, based on that, the next symbol in the upper row is detected, and so on.

The two computing procedures in the K-best algorithms are

1) *Expansion*: The K-best algorithm in the complex domain can be expressed as K (Parents of each level) $\times M$ (Children per parent). KM children should be enumerated, which results in higher computational complexity. The relaxed K-best algorithm and base-centric search methodology [10] based on Quadrature Phase Shift Keying (QPSK) modulation [11] are compared [9]. These modulation schemes do not scale linearly with the constellation size and the performance loss that occurs in these schemes is compared to the K-best algorithm. In the on demand expansion scheme the nodes are expanded by considering all the nodes with PED, which in turn reduces the performance for higher order constellations.

2) *Sorting*: In the K-best algorithm, for each level of the complex-domain, KM children should be sorted. In [12] and [13], most of the sorting schemes such as bubble sorting [14], which is sorting mechanism on the basis of Schnorr-Euchner (SE) technique [15], and a distributed sorting scheme are compared. But these techniques take high time for large values of the K and M or it will have a performance loss.

To overcome the above two challenges the MPED based K-best algorithm is proposed, in which the node with the minimum PED is considered as the parent node at each level. The computational complexity and performance will be better than the on-demand expansion scheme and works well for any values of K and M without any performance loss.

3. Proposed MPED Based K-Best Algorithm

The proposed MPED based K-best algorithm is based on the Breadth-first tree search method. The algorithm is

initialized by considering the level l of the trees and assumes the candidate nodes in the level $l + 1$ is known in the tree. The individual nodes in the level K_{l+1} will be having $\sqrt{M}$ possible children's and the K value or number of cycles will also be based on the square root of constellation order, so there will be $\sqrt{K} \times \sqrt{M}$ possible children in the tree.

The main objective of the proposed scheme is to find the First Best Child (FBC) of the initial parent node, based on the Minimum PED of the received first $\sqrt{M}$ children. Assuming that initial parent node is non-numerical value. In other words, the key innovation behind the proposed MPED based K-best algorithm is to find the FBC of each initial parent node in the level K_{l+1}, and among these children the best candidate at level K_{l+1}, is the one which is having the minimum PED value. The best candidate selected act as a parent node for the next level. The children's for the second level parents are generated and it replaces the first level siblings. In order to find the best path the process is repeated K times. For each level of tree the same procedure is repeated till the best path is found.

The proposed MPED based K-best algorithm scheme is diagrammatically represented in **Figure 2** for level l which includes the modulation order $M = 64$, so the total number of levels are given by $\sqrt{M} = 8$, and the $K = 8$. It shows the way of deriving the K_l from K_{l+1} level. The input to the algorithm is initially applied with zero PED value, the parent node at the level K_{l+1} has four children's, the corresponding PED values of the four children's are shown in **Figure 2**.

Here the parent can find its own children's without visiting all the nodes in the tree. Let the representation of S_l consist of best selected child for the first parent, and let P_T represents the corresponding PED values (in **Figure 2**, $\left\{ S_{14}^1 = -3 + 1i \right\}$ and $\left\{ P_{14}^T = 1.2766 \right\}$, where S_{ij} represents the jth child of the ith parent node in the first level of the algorithm). From **Figure 2**, it is noted that the child with lowest PED value is certainly the best child selected at the level 1. Similarly the above steps are followed for all the levels. Finally the best child is obtained based on the MPED based K-best algorithm.

The proposed scheme involves the following features:

1) It can be easily adapted to real domain.

2) Based on the QAM constellation size the K value is chosen in proposed scheme so as compared to the existing algorithm (K value is randomly chosen) it has less computational complexity.
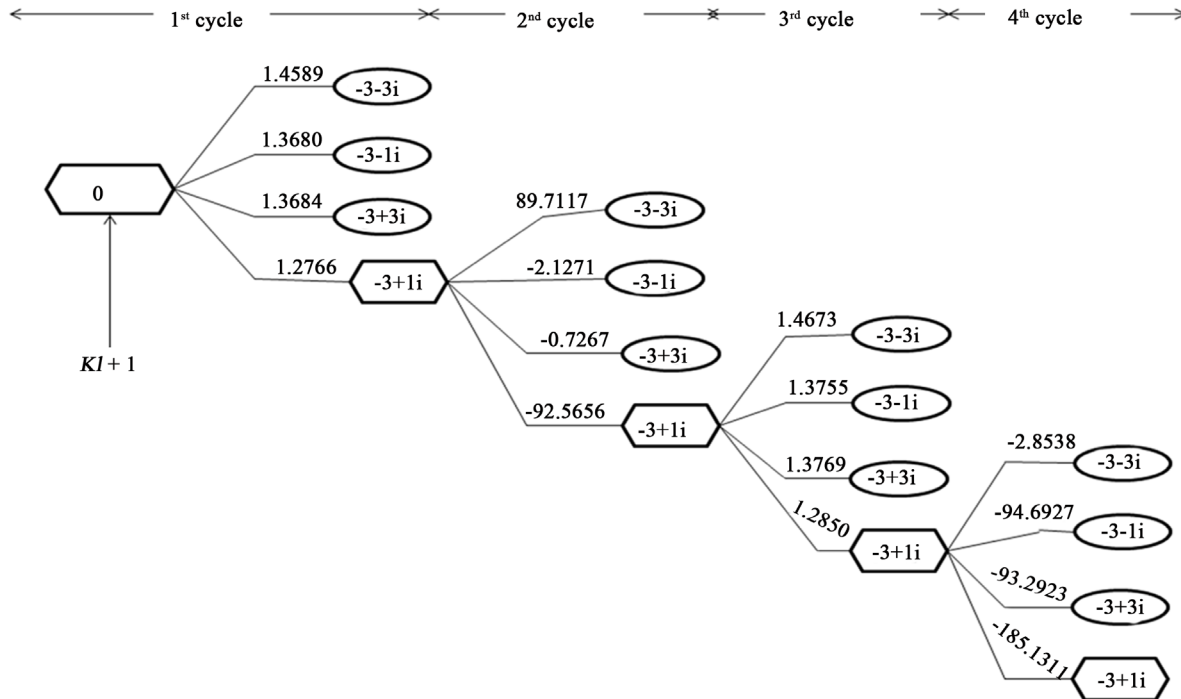

Figure 2. The proposed MPED based K-best algorithm for $\sqrt{M}=8$ and $K=8$ and simulated PED values.

3) It can be applied to infinite lattices and be jointly applied with lattice reduction.
4) Increased performance is obtained by using Wavelet Packet Transformation (WPT) with the AWGN channel.
5) It has reduced BER.
6) Easily implemented in VLSI architecture.

4. Proposed VLSI Architecture

In VLSI architecture one of the main key challenges is to achieve high throughput with minimum number of levels that are being used in the architecture. To address this challenge, a pipelined structure is used, which performs the child expansion and minimization in a pipelined fashion and the sorting is implemented in a distributed way. The pipelined architecture involves the sorter block which sorts all the signals and the Processing Element (PE) block generates the best signal from the sorted signals.

The proposed pipelined VLSI architecture for a 4×4, 64-QAM hard output MIMO detector is shown in **Figure 3**. Each layer gets the entries of z_i, r_{ij} and the K parents [16] of the previous layer as inputs and generates the K parents of the next layer as outputs. The proposed architecture consists of eight layers ($2N_t = 8$ stages), from L1 to L8, corresponding to the 8-level detection tree.

From the MPED based K-best algorithm, the best signal is detected and this signal is taken as an input to the 8th level of the tree, which opens up all the possible values in $O = \{-3, -1, 1, 3\}$ and calculates their corresponding PED [9]. The output of this stage is resulting in PED values, which is performed by Level I and for each of the nodes, the First Child (FC) is found and its PED value is updated using Level II.

4.1. Sorter Block

Using the Sorter block the FC is sorted and from that the child with lowest PED is determined. This is represented y **Figure 3**, which includes four clock cycles and all eight resulting PEDs is sorted out. The number of clock cycles required for sorting is partial than the classic bubble sort in [14]. The key idea that makes this sorter faster is the implementation of two tasks in one clock cycle through the introduction of intermediate registers. The output from the sorter block is loaded simultaneously to the PE I block.

4.2. PE I Block

The PE block contains a data register file and three computation units: an arithmetic/logic unit, a multiplier and a shifter. The PE I block takes the FC of each level as an input and generates the K-best candidate of that level one-by-one. The node with the lowest PED is definitely one of the K-best candidates in L7. This value is passed to the PE II block in L6. By removing the first child, its next sibling is calculated by the PE I block. The PED of this sibling is compared with other FCs, already present in that stage. The next K-best candidate with the lowest PED among this new set were found. This process is repeated 8 times (taking 8 cycles) until all the K-best values of the second level of the tree are generated and passed to the PE II block.
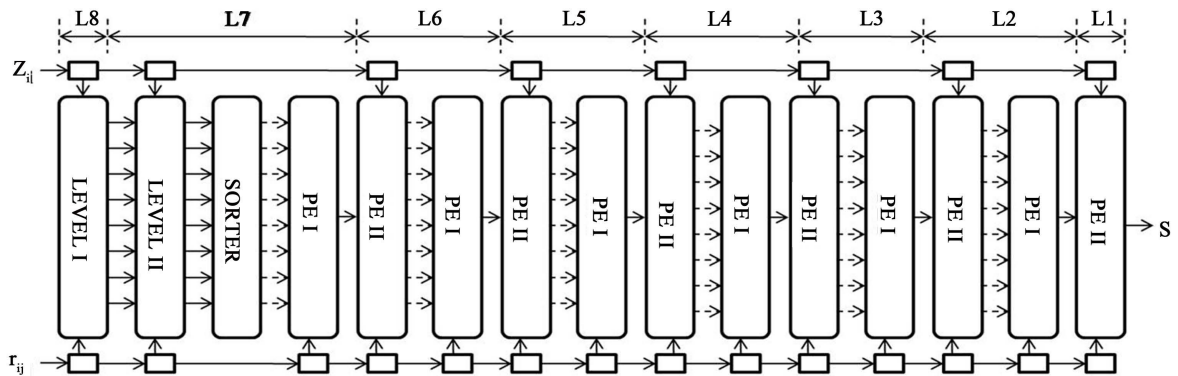

Figure 3. Proposed Pipelined VLSI architecture of the MPED based K-best algorithm for the detection of a 4×4, 64-QAM system with $K = 8$.

4.3. PE II Block

The PE II block receives the K-best candidates of L7, one after the other, and generates the FC of each received K-best candidate one-by-one and sorts them as they arrive. It finally transfers them to its following PE I block. This process repeats for all the levels down to the first level. Since at the first level only the FC with the lowest PED is of concern, whose solution S is the hard-decision output of the detector.

5. Simulation Results

A 4 × 4 64-QAM MIMO system with K = 8 is considered in our simulation. The simulation is carried out using Matlab. The input message signal is chosen and it can be plotted in the random bit form. To apply the proposed method for the input message signal, the best candidates are identified for each cycle.

5.1. Best Candidates for the Proposed Detection Algorithm

The best candidates for the proposed MPED based K-best algorithm obtained as a result of simulation for the given input message stream are listed below.
1) The best candidate of 1 cycle is 3.283351e+003.
2) The best candidate of 2 cycle is −1.083299e+002.
3) The best candidate of 3 cycle is 3.279795e+003.
4) The best candidate of 4 cycle is −2.166598e+002.
5) The best candidate of 5 cycle is 3.393075e+003.
6) The best candidate of 6 cycle is −3.249897e+002.
7) The best candidate of 7 cycle is 3.389520e+003.
8) The best candidate of 8 cycle is −4.333195e+002.

5.2. BER Performance Analysis for Proposed Algorithm with Rayleigh and AWGN Channel

Based on BER vs. SNR the simulation results of the MIMO detections are presented in this section. BER is a key parameter that is used in assessing systems that transmit digital data from one location to another. It is defined as,

$$BER = \text{number of errors/total number of bits sent} \qquad (4)$$

If the medium between the transmitter and receiver is good and the signal to noise ratio is high, then the bit error rate will be very small possibly insignificant and having no noticeable effect on the overall system However if noise can be detected, then there is chance that the bit error rate will need to be considered. The BER is compared with the Rayleigh fading channel as well as AWGN fading channel scheme as shown in **Figure 4**, with the increased SNR value from 0 to 20 dB. The analysis shows BER is less in AWGN channel with the proposed algorithm than the Rayleigh channel.
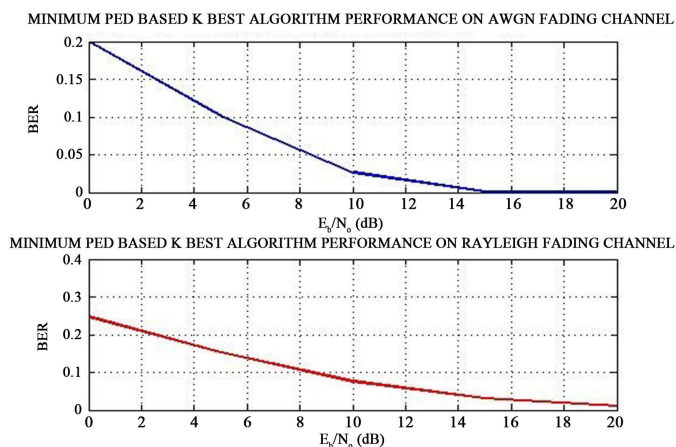

Figure 4. BER comparisons for proposed algorithm with Rayleigh and AWGN channel.

5.3. Performance Analysis of MPED Based K-Best Algorithm

In this section we compare the proposed method (MPED based K-algorithm) with the existing MIMO detection algorithms such as ZF, MMSE-SIC and ML. The MPED based K-best algorithm gives reduced BER as compared to ZF and MMSE-SIC detector algorithms as shown in **Figure 5**. Also its result is close to ML detection method. It shows that the performance of the proposed method is close to optimum ML detection method.

5.4. BER Comparison for FFT and WPT on Proposed Algorithm

Fast Fourier Transform (FFT) is a powerful tool for analyzing the components of a stationary signal (no change in the properties of signal). But it is less useful in analyzing non-stationary signal (change in the properties of signal). Wavelet Packet Transforms allows the components of both stationary and non-stationary signals to be analyzed. The main difference is that wavelets are well localized in both time and frequency domain whereas the Fourier transform is only localized in frequency domain. The BER is compared for both FFT as well as WPT [11] as shown in **Figure 6**. From the figure the Wavelet scheme produces a less BER irrespective of the SNR, than the FFT scheme. So WPT transformation technique is used in our proposed method for processing the signal.

6. Complexity Analysis

The proposed complex MIMO detector and the recently proposed MIMO detectors in the real and complex domains which were compared and reported in the literature is shown in **Table 1**. This comparison suggests that the proposed scheme has the high performance *i.e.*, higher throughput, lower area, lower energy and lower latency compared to all the reported real and complex-domain VLSI realizations.

This design has a larger core area than the one in [9], which is related to the nature of the complex-domain implementation and extra resources for the complex-domain calculations. Thus the major difference between all of these schemes, including the one in this paper, is the way the detection algorithm is implemented, which translates to different throughput and hardware complexity. It is shown that the proposed algorithm is imple-

Table 1. Design comparison of the current VLSI implementations for 4×4 MIMO detectors.

| References	TCAS-II 2010 [17]	DATE 2009 [18]	TVLSI 2010 [19]	JSSC 2010 [20]	JSSC 2011 [21]	TVLSI 2011 [22]	TVLSI 2011 [9]	TVLSI 2013 [5]	Proposed Work
Modulation	16-QAM	64-QAM	64-QAM	(4-64) QAM	64-QAM	(16-64) QAM	64-QAM	64-QAM	64-QAM
Antenna	4×4	4×4	4×4	4×4 - 8x8	4×4	4×4	4×4	4×4	4×4
Method	SISO-SD	Sys. Like Detection	K-Best	MBF-FD(SD)	SISO MMSE PIC	MMF-LSD	K-Best	Modified K-Best	MPED based K-Best
Domain	Complex	Complex	Real	Complex	Complex	Real	Real	Complex	Complex
K-value	N/A	N/A	5-64	N/A	N/A	N/A	10	10	8
Process size	90 nm	45 nm	65 nm	0.13 µm	90 nm	0.18 µm	0.13 µm	0.13 µm	0.13 µm
f_{max} (MHz)	250	574.7	158	198	568	250	282	417	435
Throughput (Mb/s)	90	215	732 - 100	285 - 431	757	31.7 - 146.3	675	1000	1100
Gate count (kG)	96	33.1	1760	350	410	25.4 - 48.2	114	340	328
NHE	1.6	0.45	4.81 - 35.2	1.23 - 0.81	0.78	0.58 - 0.24	0.17	0.34	0.3
Energy/bit	N/A	N/A	N/A	N/A	250 PJ/b	N/A	200 pJ/b	110 pJ/b	100 pJ/b
Power (mW)	N/A	N/A	165	57-74	189.1	57-90	135	1700	1684
Latency (µs)	N/A	N/A	N/A	N/A	N/A	N/A	0.6	0.36	0.27
Hard/soft	Soft	Soft	Hard	Soft	Soft	Soft	Hard	Hard	Hard
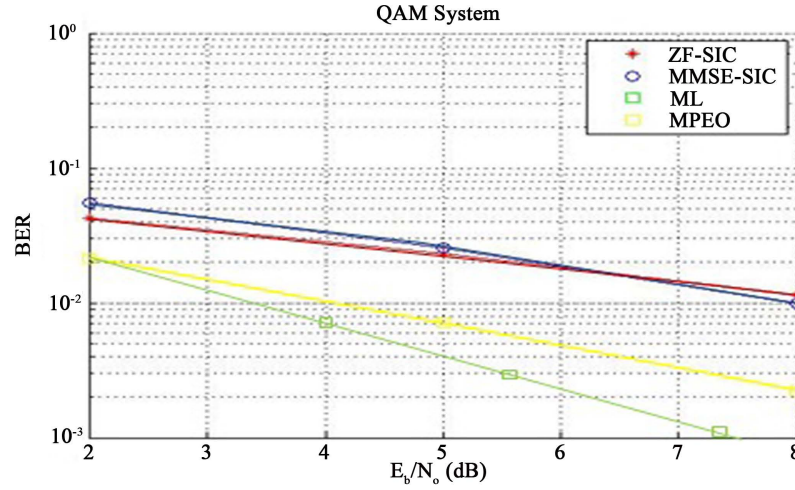
Figure 5. Analysis of MPED based K-best algorithm with various detection algorithm.
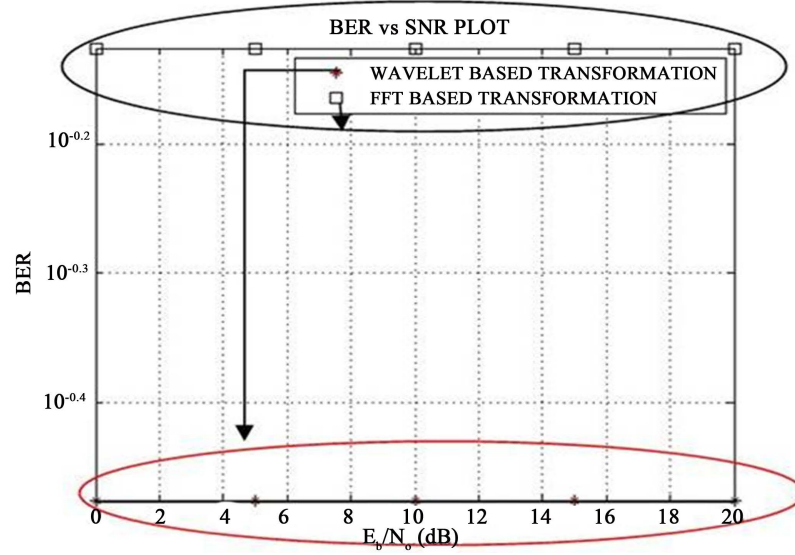

Figure 6. BER comparison for FFT and Wavelet scheme.

mented using a feed forward architecture. According to the proposed algorithm, K-best candidates of each layer of the architecture are generated in Kclock cycles, which increase the throughput of the system.

The throughput of the system is the number of packets produced per unit time. This is measured in units of whatever is being produced (I/O samples, memory words, iterations) per unit time. The latency is the number of cycles required for the system to accept next input and the gate count involves the total core area of the design.

The Normalized Hardware Efficiency (NHE) is calculated, which is given by the gate count and the corresponding scaled throughput [5] in the same technology for all designs. So

$$\text{NHE}\left(\text{kG/Mb/ps}\right) = \frac{\text{core area}\left(\text{kG}\right)}{\text{scaled throughput}\left(\text{Mb/s}\right)} \tag{5}$$

Moreover, the proposed scheme is implemented in the FPGA platform. The synthesis results and the required resources for the 4×4, 64-QAM MIMO detector using the proposed scheme is shown in **Table 1**.

7. Conclusion

To detect the best signal for high performance MIMO detector, a MPED based K-best algorithm has been pro-

posed. This proposed algorithm is scalable both in terms of number of transmitting/receiving antennas and the constellation size. It gives a reduced BER and low computational complexity as compared to existing algorithms. This is carried out by simulating both in terms of FFT scheme and wavelet scheme using Matlab. The proposed design was implemented in Virtex-5 FPGA from Xilinx platform; it provides a high throughput of 1.1 Gigabits per second (Gb/s) at 435 MHz with the area of 328 K gates in a 0.13-µm VLSI process. This algorithm is applicable for real time wireless communication.

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