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A 4x4 MIMO-OFDM Low Complexity Receiver using Novel Detection Algorithms for future generation Wireless Applications

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Abstract— The Multiple Input Multiple Output Orthogonal Frequency Division Multiplexing Technology (MIMO-OFDM) may become an inevitable contender for being deployed in almost all types of future generation wireless communication systems for attaining high spectral efficiency at extremely high throughput. The technical constraint in realization of such systems is high computational complexity of the detector when designed for higher order MIMO with 64-QAM & 256 QAM. This paper presents design and development of a novel detection algorithm based on Adaptive Sphere decoding technique to realize a low complexity 4x4 MIMO-OFDM receiver.

The new algorithms are tested with LTE standards on MATLAB platforms, have shown significant reduction in computational complexities in terms of number of nodes traversed, Flops, Complex Multiplications, etc, and still performing at par with optimal detectors. The proposed detection algorithms may serve as one of the strong contenders to be deployed in future generation wireless standards.

Keywords—MIMO, OFDM, receiver, detection,

I. Introduction

MIMO systems are known to offer very high data rate for wireless communication. The ever increasing need of high data rate in wireless scenario can be met only by using multiple input-output media. The major challenge in deploying such high data rate systems is the receiver complexity which increases with increasing I/O terminals and higher modulation orders [1].

To be able to practically use large MIMO systems, the receiver complexity must be reduced. Major cause of complexity at receiver end is the MIMO symbol detection which directly depends on number of antennas and modulation order. The optimal detection algorithm i.e. the maximum likelihood detection (ML) is too complex to be implemented practically, so several near optimal algorithms were developed [2].

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Among the prevailing near optimal detection algorithms, sphere decoding claims to achieve near ML performance at much reduced complexity. However, it still offers very high complexity at higher order modulations.[3]

Sphere decoder looks for correct symbol only within a sphere of a certain radius around received symbol rather than looking into the entire symbol space as in the case of ML detection. Mathematically[3],

$$\| y - Hx \|^2 < c^2 \qquad (1)$$

Where 'y' is the received symbol vector, 'x' is the transmitted vector, 'H' is the channel matrix and 'c' is the radius of sphere. , Although this approach achieves a considerable reduction in complexity, but for 64/256-QAM modulations, traversing the symbols inside the sphere may also account for large number of traversals and thus higher mathematical complexity[3].

This paper presents a low complexity receiver design using MIMO-OFDM, which can be employed in communication systems where high data rate is required. Section II presents the receiver design with explanation of various building blocks.

Section III presents the proposed low complexity detection algorithms to be used in the receiver. Section IV gives results and discussions and the paper is concluded in section V.

II. Receiver Design

Fig. 1 shows the block diagram of the proposed MIMO receiver.

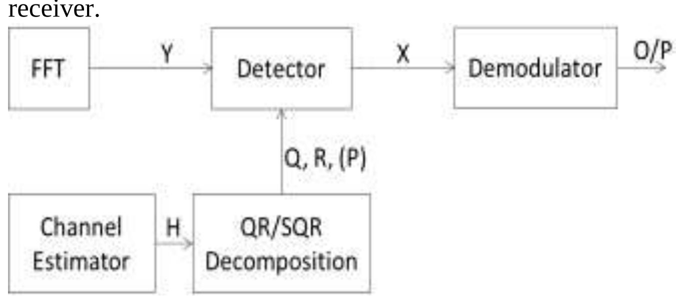


Figure 1. Block Diagram of the MIMO receiver

FFT: Fast Fourier Transform is performed at every receiver antenna terminal to invert the IFFT performed over symbols at transmitter end. IFFT is performed to meet the requirement of multi carrier modulation where multiple oscillators at different frequencies are required [4].

Chanel Estimator: The proposed receiver uses semi-blind channel estimation technique.

Semi-blind channel estimation schemes use a few training symbols to provide the initial MIMO channel estimation and exchange the information between the channel estimator and the data detector iteratively [5].

Several solutions have been proposed to minimize the computational cost, and hence the energy spent in channel estimation of MIMO systems. In [6], a novel method of minimizing the overall energy consumption is presented. In [7], a better performance and reduced complexity channel estimation method is proposed for MIMO systems based on matrix factorization. This technique is applied on training based Least Squares (LS) channel estimation for performance improvement. The proposed receiver uses the channel estimator proposed by [7].

QR/SQR Decomposition: Before applying the detection algorithm, the channel matrix H is decomposed using QR-Decomposition or Sorted QR Decomposition.

QR decomposition is the process of decomposing channel matrix H into matrices Q and R such that $H = Q\begin{bmatrix} R \\ 0_{(N_R - N_T)\times N_T} \end{bmatrix}$ where Q = [Q_1Q_2], is an $N_R \times N_R$ unitary matrix and R is an $N_T \times N_T$ upper triangular matrix. Performing QR decomposition on channel matrix H will give[8]

$$H = QR \qquad (2)$$

A MIMO system is represented as

$$y = Hx + n \qquad (3)$$

Hence by equation (2) & (3)

$$y = QRx + n$$

$$Q'y = Q'QRx + Q'n$$

$$\hat{y} = Rx + Z \qquad (4)$$

Mathematically, noise at the receiver end can be expressed (from equation (4)) as:

$$Z = \hat{y} - Rx \qquad (5)$$

After QR-decomposition, if equation (5) is represented graphically, it will take the form of a tree structure, as shown in figure 1. The respective errors at every layer are calculated by calculating norm between nodes at two layers. Figure 1 also shows how a radius constraint is applied on the tree. The number of layers in the tree represents order of R matrix and thus the order of MIMO system.

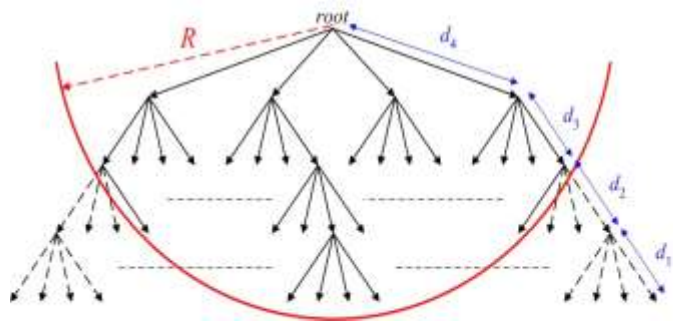


Figure 2. Tree structure obtained via QR decomposition of H

Sorted QR Decomposition arranges the signals of each layer in decreasing order of SNR. Thus, during tree traversal, symbols with higher SNR are encountered first thereby increasing the chances of correct detection and early tree termination [8].

The pseudo code of Sorted QR decomposition is given as[9]:

(1) $R = 0, Q = H, P = eye(N_T)$
(2) $For\ i = 1,2,3, \dots N_T$
(3) $K_i = arg\ min\ ||q_j||$
(4) $exchange\ columns\ i\ and\ K_i\ in\ Q, R\ and\ P$
(5) $r_{i,j} = ||q||$
(6) $qi = \frac{q_i}{r_{ij}}$
(7) $for\ j = i + 1 \dots N_T$
(8) $r_{i,i} = q_i^H q_j$
(9) $q_j = q_j - r_{i,j}\, q_i$
(10) end
(11) end

Detector: Detector performs the detection of correct MIMO symbols from the received symbol vector. The received symbol contains the effect of channel and noise of environment and various components at transmitter as well as receiver end. Their effect is nullified and the correct symbol is detected using suitable algorithms. The proposed receiver employs two different algorithms which were derived from the sphere decoding algorithm. These algorithms are discussed in the next section of this paper.

Demodulator: The detected symbol is then demodulated to regenerate the transmitted bits. This is usually M-QAM demodulator. The proposed receiver is tested using 16-QAM and 64-QAM demodulators [9].

Fig. 3 shows the wireless receiver setup, used to verify the simulated results.

Figure 3. Setup of wireless transreceiver

V. Detection Algorithms

The detection algorithm is designed by modifying the sphere decoder algorithm. The sphere decoding algorithm with adaptive radius is used, i.e. whenever a leaf node is detected, the search radius is reduced to the error of that node and rest of the tree is traversed with reduced sphere radius. Two variations of adaptive radius sphere decoding algorithm were proposed. These 2 variations were called as ARSD-SQRD and ARSD-K Best respectively

a.) Adaptive Radius Sphere Decoding Algorithm using Sorted QR Decomposition (ARSD-SQRD): Sorted QR Decomposition makes sure that the signals of each layer are ordered with the SNR from high to low, so that the SD algorithm can prior detect the signals which own the maximum SNR. Due to this measure, SD algorithm doesn't need to detect the signals with low SNR and this help to increase the possibility of algorithm searching paths be cut off so that the calculation complexity can be decreased.

The proposed algorithm is as follows:

Step 1: Set an initial sphere radius $'c_o'$

Step 2: Perform sorted QR Decomposition on channel matrix

$$H = PQR$$

Step 3: Begin sphere decoding by comparing error 'err' of respective nodes with sphere radius.

$$\|\hat{y} - Rx\|^2 \leq c_o^2$$

Step 4: If the error is less than the sphere radius $'c_o'$.proceed to lower layers else proceed to the next node in the same layer.

Step 5: If a leaf node is detected, replace the sphere radius with the error of this node i.e.

$$c_i = \text{err}$$

Step 6: Repeat step 3 & Repeat step 3 to 5 until all eligible nodes are traversed.

$$\|\hat{y} - Rx\|^2 \leq c_i^2$$

Step 7: Find out the node with minimum error & multiply it with P to obtain the solution

$$s_{ML} = min(\|\hat{y} - Rx\|^2) * P$$

The ARSD-SQRD optimizes the tree to reduce the adaptive radius to minimal value. One more parameter which can be optimized is initial radius of the tree. To decide a radius large enough to find a solution and yet small enough to not visit too many nodes, the best practice would be to determine the radius value from the tree itself. Considering this fact, we propose another modification in the ARSD-SQRD Algorithm.

b.) Adaptive Radius Ordered Sphere Decoding Algorithm with Initial Radius By K-Best (ARSD-K Best):

Here, we use K-Best detection method for first symbol. The error obtained in the detected symbol is then used as initial radius for the remaining symbols. Depending upon the channel condition, this radius may be varied from R to 2R.

The proposed algorithm is as follows:

Step 1: Perform sorted QR Decomposition on channel matrix.

$$H = PQR$$

Step 2: Select an initial value for K (generally K = $\sqrt{M}$ where M is the modulation order).

Step 3: Perform K-Best Detection for first symbol

Step 4: Define initial radius based on the error obtained in the detected symbol

$$c_o \in (R, 2R)$$

Step 5: Begin sphere decoding by comparing error 'err' of respective nodes with sphere radius.

$$\|\hat{y} - Rx\|^2 \leq c_o^2$$

Step 6: If the error is less than the sphere radius 'c_o' proceed to lower layers else proceed to the next node in the same layer.

Step 7: If a leaf node is detected, replace the sphere radius with the error of this node i.e

$$c_i = \text{err}$$

Step 8: Repeat step5 to 7 until all eligible nodes are traversed.

$$\|\hat{y} - Rx\|^2 \leq c_i^2$$

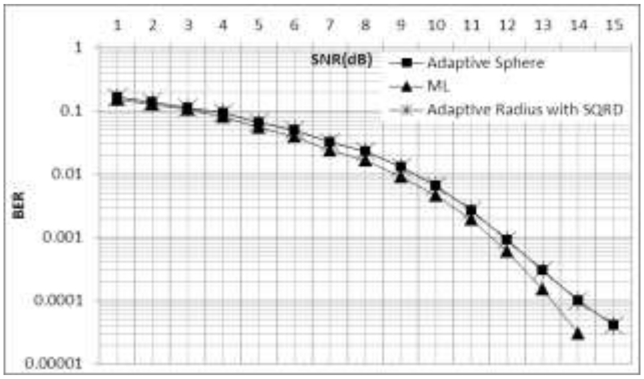
Step 9: Find out the node with minimum error & multiply it with P to obtain the solution

$$s_{ML} = min(\|\hat{y} - Rx\|^2) * P$$

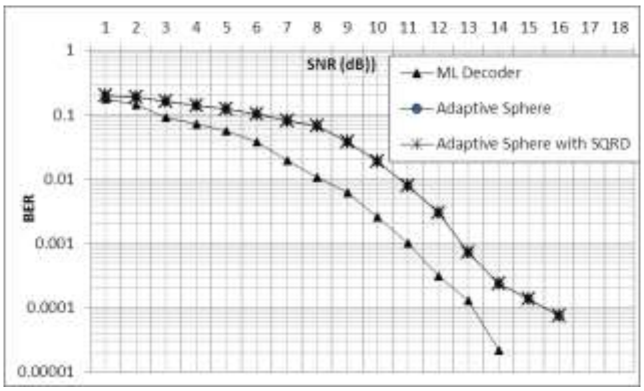
Here s_{ML} is the detected symbol.

VI. Results & Discussion

Both the algorithms were implemented and observations were taken in simulated LTE extended pedestrian A model environment with Doppler shift of 5Hz. Figure 4 shows the BER vs. SNR curve for ARSD-SQRD algorithm. It reveals that for 16-QAM, the algorithm achieves BER of 1% at 11 dB SNR while ML achieves the same at 10dB SNR. The BER performance plot for 64-QAM also depicts the same behavior, here a reasonable BER of 1% is achieved at 11 dB SNR.



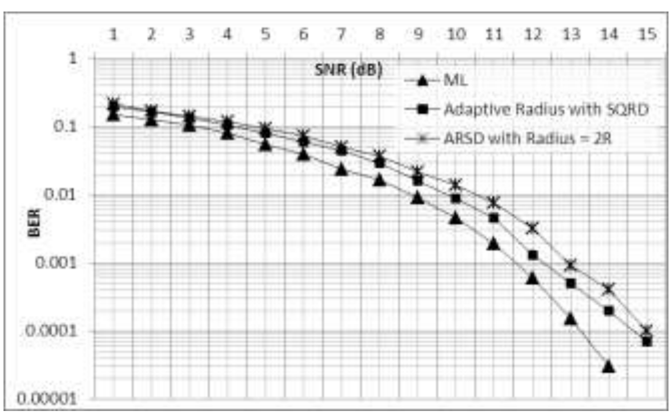
(a)



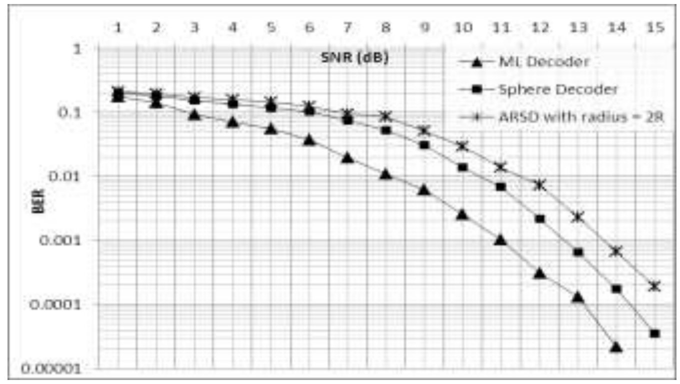
(b)

Figure 4. BER Vs. SNR for ARSD-SQRD on 4x4 MIMO (a) 16-QAM (b) 64-QAM

Figure 5.a shows BER vs. SNR curve for ARSD-K Best algorithm at 16-QAM. It clearly shows that the proposed algorithm achieves a reasonable BER of 1% at 11dB SNR as compared to 10dB for ML detection. Figure 10.b also shows the same characteristics for 64-QAM modulation scheme. Here, BER of 1% is achieved at 14dB as compared to 13dB for conventional sphere decoder and 11dB for ML Detector.



(a)



(b)

Figure 5. ER Vs. SNR curve for ARSD-K Best with radius = 2R for 4x4 MIMO (a) 16-QAM (b) 64-QAM

Fig. 6 & Fig. 7 shows throughput achieved for LTE EPA 5 Hz for 4x4 MIMO, 64-QAM configuration by ARSD-SQRD ARSD-K Best algorithms respectively.

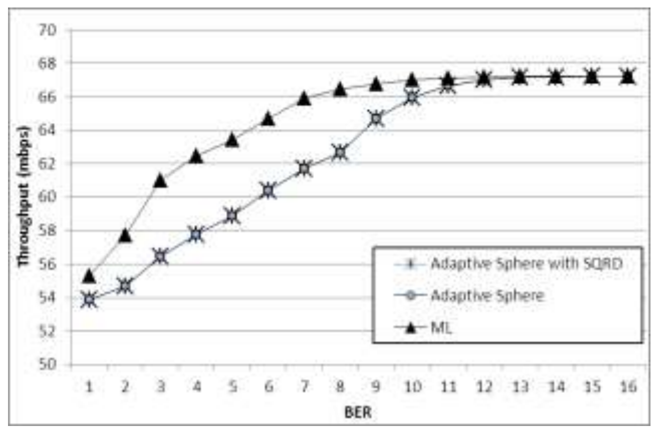


Figure 6. Throughput vs. SNR curve for ARSD-SQRD algorithm

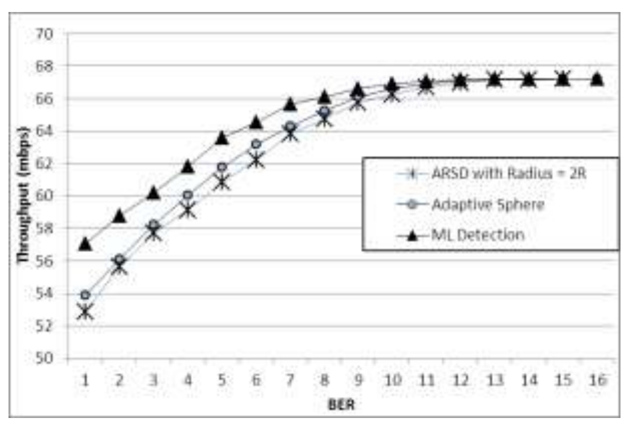


Figure 7. Throughput Vs. SNR curve for ARSD-K BEst algorithm

It reveals that the ARSD-SQRD algorithm underperforms ML detector at low SNR, but achieves peak throughput of 67.2 mbps which is nearly equivalent to the ML detector at SNR of

12dB. However, the throughput is same as achieved with the sphere decoder algorithm due to same BER performance of both the algorithms.

Similarly, the ARSD-K Best algorithm initially provides low throughput owing to its comparatively higher BER but as we move to the higher SNR region, peak throughput equivalent to the ML detector is achieved. This throughput variation can be directly inferred from the BER performance of algorithms.

Complexity Analysis: Table I shows a comparison between the conventional and ARSD-SQRD algorithm on the basis of complexity parameters at 4x4 MIMO with 64-QAM modulation. It reveals that the algorithm reduces the average number of visited nodes by 32.46% as compared to the conventional sphere decoder. Also, number of complex additions and multiplications is reduced by 34.31% and 31.70% respectively.

TABLE I. COMPLEXITY COMPARISON BETWEEN CONVENTIONAL ALGORITHMS AND ARSD-SQRD AT 4X4 MIMO 64-QAM

	Adaptive Radius SD	ARSD with SQRD & initial radius = 2R	Reduction
No. of Complex Multiplications	4049.352	2734.545	32.46%
No. of Complex Additions	2800.345	1839.344	34.31%
No. of Nodes Traversed	1140.102	778.621	31.70%

Table II shows a comparison between the ARSD-SQRD and ARSD-K Best algorithms on the basis of complexity parameters. It reveals that the proposed algorithm reduces the average number of visited nodes by 47.59% as compared to the sphere decoder. Also, number of complex additions and multiplications is reduced by 41.24% and 53.28% respectively when compared with the sphere decoder.

TABLE II. COMPLEXITY COMPARISON BETWEEN CONVENTIONAL AND ARSD-K BEST AT 4X4 MIMO 64-QAM

	Adaptive Radius Sphere Decoder	ARSD with SQRD & initial radius = 2R	Reduction
No. of Complex Multiplications	4049.352	2122.234	47.59%
No. of Complex Additions	2800.345	1645.344	41.24%
No. of Nodes Traversed	1140.102	532.621	53.28%

VII. Conclusion

The proposed MIMO-OFDM receiver with semi blind channel estimation and two novel detection algorithms is tested for LTE EPA 5Hz environment and its performance is found at par with the conventional near optimal algorithms. Inferring from the results, it can be concluded that both the proposed algorithms offer performance similar to the sphere decoder but offer less complexity. However, the ARSD-K Best offers least complexity. This receiver may thus be an efficient choice to be employed in next generation wireless communications.

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