Analysis of Improved Square-Root Algorithm Based on Efficient Inverse Cholesky Factorization for V-blast MIMO Wireless Communications

Shankar.P [#], Dr. S.A Hariprasad *

Department of Electronics and Communication, RV College of Engineering, Bangalore 560059, Karnataka India
[#]shankar19388@ymail.com ; [*] hariprasad@rvce.edu.in ;

Abstract Vertical Bell Laboratories Layered Space time (V-BLAST) detection schemes are widely used in time critical application involving high speed packet transfer using MIMO for 3GPP and 3GPP-2 standards. As the number of transmitting and receiving antennas is increased, employing efficient square root algorithm yields high computational cost due to the inefficient utilization of orthogonal or unitary transformations and discarding intermediate results without any usage. Reduction in the computational cost is achieved by improved square root algorithm which utilizes intermediate results that were discarded without any usage in the original square-root algorithm. Further reduction in computational cost can be achieved by employing a fast algorithm for inverse Cholesky factorization used to compute a triangular square-root of the estimation error covariance matrix which is then applied to improved square-root algorithm. This paper compares the performance between the improved square root algorithm with minimum mean square error (MMSE) filter and an Improved Square-Root Algorithm Based on Efficient Inverse Cholesky Factorization with MMSE filter when subjected to multi-media application for various numbers of transmitting and receiving antennas with varying SNR. Performance parameters considered include bit error rate (BER), symbol error rate (SER), peak signal-to-noise ratio (PSNR), number of number of floating point operations (FLOPS), Time required for detection. The number of floating point operation (FLOPS) required for detection for improved square root algorithm based on efficient inverse cholesky factorization with MMSE for 16 transmitting and 16 receiving antennas is 0.6 x 10^6, a reduction of 2.9x10^6, 4.2x10^6, 5.4x10^6 and 5.6x10^6 is achieved when compared to improved square-root algorithm, the efficient square root algorithm and the conventional detection scheme employing Zero forcing (ZF) and MMSE filter respectively. This algorithm is faster than the existing efficient V-BLAST algorithms.

Index Terms— **Multiple-input–multiple-output (MIMO) systems, Bell Laboratories Layered Space time (BLAST), vertical BLAST (V-BLAST), Zero forcing (ZF), Bit error rate (BER), Symbol error rate (SER), peak signal-to-noise ratio (PSNR), Floating point operations (FLOPS).**

I. INTRODUCTION

Multiple-Input–Multiple-Output (MIMO) wireless systems, characterized by multiple antenna elements at the transmitter and receiver, have demonstrated the potential for increased capacity in rich multipath environments [1]–[4]. Such systems operate by exploiting the spatial properties of the multipath channel, thereby offering a new dimension which can be used to enable enhanced communication performance. Bell Labs Layered Space-Time architecture (BLAST) [5], including the relative simple vertical BLAST (V-BLAST) [6], is such a system that maximizes the data rate by transmitting independent data streams simultaneously from multiple antennas. V-BLAST often adopts the ordered successive interference cancellation (OSIC) detector [6], which detects the data streams iteratively with the optimal ordering. In each iteration the data stream with the highest signal-to-noise ratio (SNR) among all undetected data streams is detected through

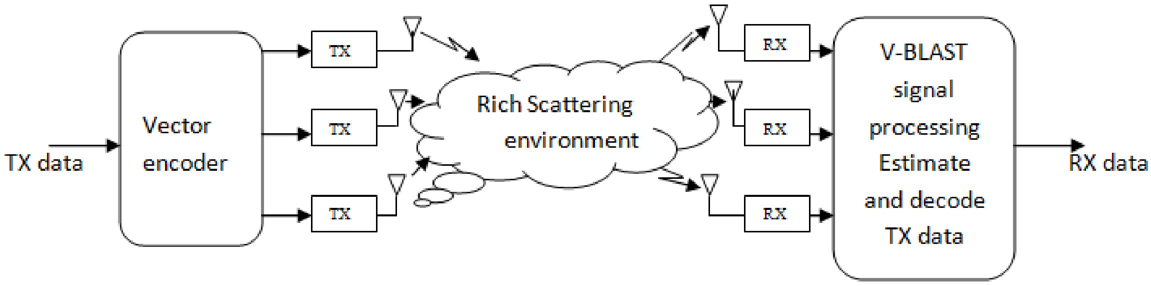


Figure 1: V-BLAST system model

Zero-forcing (ZF) or minimum mean square error (MMSE) filter. This is referred to as *nulling and cancellation*. The optimal detection order is from the strongest to the weakest signal, since this minimizes propagation of error from one step of detection to the next step. Further the effect of the detected data stream is subtracted from the received signal vector. This is referred to as *interference cancellation.*

It turns out that the main computational bottleneck in the conventional detection algorithm is the step where the optimal ordering for the sequential estimation and detection of the transmitted signals, as well as the corresponding so called *nulling vector* is determined. Current implementations devote 90% of the total computational cost to this step. This high computational cost limits the scope of the application that admits inexpensive real time solutions. Moreover, when the numbers of transmitting and receiving antennas are large repeated pseudo-inverse that conventional detection algorithm requires can lead to numerical instability, thus a numerically robust and stable algorithm is required. In an attempt to reduce the computational complexity an efficient square-root [7-8] algorithm has been proposed. The algorithm is numerically stable since it is division free and uses only Orthogonal transformations such as Householders transformation or sequence of Givens Rotation[9][10]. To further reduce the computational cost An Improved square root algorithm has been proposed [11] which speed up's the original square root algorithm by 45% in terms of number addition and multiplication by reusing intermediate results. An Improved Square-Root Algorithm for V-BLAST Based on Efficient Inverse Cholesky Factorization [12] computes a triangular square root of the estimation error of the covariance matrix using Inverse Cholesky Factorization and is then applied to An Improved square root algorithm which can offer further computational savings. The algorithm is faster than the existing efficient V-BLAST detection algorithms.

The goal of this paper is to provide a performance comparison between the Improved square root algorithm and Improved square root algorithm based on Efficient Inverse Cholesky Factorization when subjected to multi-media application for various numbers of transmitting and receiving antennas with varying SNR. Parameters considered include BER, SER, PSNR, FLOPS, Time required for detection.

The remainder of the paper is organized as follows Section II describes the V-BLAST system model Section III introduces different V-BLAST detection schemes which include Improved square root algorithm with minimum mean square error (MMSE) filter and an Improved Square-Root Algorithm Based on Efficient Inverse Cholesky Factorization with MMSE filter, along with their simulation results. Finally we make conclusion in Section IV.

In the following sections, $(\cdot)^T$, $(\cdot)^*$ and $(\cdot)^H$ denote matrix transposition, matrix conjugate, and matrix conjugate transposition, respectively. 0_M is the $M \times 1$ zero column vector, while I_M is the identity matrix of size M.

II. SYSTEM MODEL

V-BLAST system consists of M transmitting and N receiving antennas in a rich-scattering environment illustrated in Figure. 1 where a single data stream is de-multiplexed into M sub streams and each sub stream is then encoded into symbols and fed to its respective transmitter. The Transmitters 1 to M operate co-channel at symbol rate $1/T$ symbols/sec, with synchronized symbol timing. Each transmitter is itself an ordinary QAM transmitter. The collection of transmitters comprises, in effect, a vector-valued transmitter, where components of each transmitted M-vector are symbols drawn from a QAM constellation. The power launched by each transmitter is proportional to 1/ M so that the total radiated power is constant and independent of M.

Let the Signal vector (s) transmitted from M antennas be $s = [s_1, s_2, \ldots s_M]^T$ with the co-variance $E(ss^H) = \sigma_s^2$.Then the received vector (x) is given by

$$x = H.s + v, \qquad (1)$$

Where v is the N×1 zero-mean circular symmetric complex Gaussian (ZMCSCG) noise vector with the zero mean and the covariance σ_v^2 I_N and $H = [\, h_1, h_2 \ldots h_M] = [\, \underline{h}_1 \; \underline{h}_2 \ldots \underline{h}_M \,]^H$ is the N×M complex matrix h_m and $\underline{h}_m$ are the mth column and the nth row of H, respectively.

The Linear zero-forcing (ZF) estimate of s is

$$\hat{s} = H^+ x = (H^H H)^{-1} H^H x. \qquad (2)$$

Define $\alpha = \sigma_v^2 / \sigma_s^2$. The Linear minimum mean square error (MMSE) estimate of s is

$$\hat{s} = (H^H H + \alpha I_M)^{-1} H^H x. \qquad (3)$$

Let $R = (H^H H + \alpha I_M)$.Then the estimation error covariance matrix [6] P is given by

$$P = R^{-1} = (H^H H + \alpha I_M)^{-1} \qquad (4)$$

The Ordered successive Interference Cancellation (OSIC) detection detects M entries of the transmit vector ‘s’ iteratively with the optimal ordering. In each iteration, the entry with the highest SNR among all the undetected entries is detected by a linear filter, and then its interference is cancelled from the received signal vector [5].

Suppose that the entries of ‘s’ are permuted such that the detected entry is s_M ,the M-th entry. Then the Interference is cancelled by

$$x^{M-1} = x^M - h_M s_M \qquad (5)$$

where s_M is treated as the correctly detected entry and the initial $x^M = x$. Then the reduced order problem is

$$x^{M-1} = h_{M-1} s_{M-1} + v \qquad (6)$$

where the deflated channel matrix $H_{M-1} = [\, h_1, h_2 \ldots h_{M-1}]$ and the reduced transmit vector $s_{M-1} = [\, s1, s2, .. \, s_{M-1} \,]^T$.

The Linear estimate of s_{M-1} can be deduced from (6).The detection will proceed iteratively until all entries are detected.

III DETECTION SCHEMES

Improved square root algorithm and Improved Square-Root Algorithm Based on Efficient Inverse Cholesky Factorization for V-blast MIMO Wireless Communications are summarized as follows:

A. *An Improved square root algorithm for V-blast*

The previous algorithm An Efficient Square-Root Algorithm for BLAST algorithm [8] computes the whole nulling matrices Q_{α}^{m} for each deflated sub-channel matrix, while only one column of each is used (i.e., the optimum nulling vector); the intermediate results $P_M^{\frac{M-1}{2}}$ computed in the algorithm are discarded without any usage. Thus An Improved Square Root Algorithm [11] for BLAST find's the optimum nulling vectors with the help of $P_M^{\frac{M-1}{2}}$, avoiding the computation of Q_{α}^{m}. At the same time, the robustness of the improved square-root algorithm is maintained without any inverse or squaring operation.

Initialization:

1) Let $m = M$. To Compute an initial F = F

a) Set $\mathbf{P}_0^{\frac{1}{2}} = (1/\sqrt{\alpha})\mathrm{I}_M$

b) Compute $\Pi_i = \begin{bmatrix} 1 & \mathbf{h}_i^H \mathbf{P}_{i-1}^{\frac{1}{2}} \\ 0_M & \mathbf{P}_{i-1}^{\frac{1}{2}} \end{bmatrix}$ and

$$\Pi_i \Theta_i = \begin{bmatrix} x & \mathbf{0}_M^T \\ x & \mathbf{P}_i^{\frac{1}{2}} \end{bmatrix} \quad (7)$$

Iteratively for $i = 1, 2, \cdots, N$.

Where "×" denotes irrelevant entries at this time and Θ_i is any unitary transformations that block lower triangularize the pre-array Π_i.

Finally $F = \mathbf{P}_N^{\frac{1}{2}}$ is the square root of P where $P = (H^H H + \alpha I)^{-1}$

Iterative Detection:

2) Find the minimum length row of F_m and permute it to the last row. Permute H_m accordingly

3) Block upper-triangularize F_m by

$$F_m\Sigma = \begin{bmatrix} F_{m-1} & u_{m-1} \\ \mathbf{0}_M^T & \lambda_m \end{bmatrix} \quad (8)$$

Where Σ is a unitary transformation, u_{m-1} is an $(m-1) \times 1$ column vector, and λ_m is a scalar.

4) Form the linear MMSE estimate of a_m,

$$\hat{\mathbf{a}}_m = \lambda_m \left[\mathbf{u}_{m-1}^{H} \quad (\lambda_m)^* \right] \mathbf{H}_m^H r^{(m)}. \quad (9)$$

5) Obtain a_m from $\hat{\mathbf{a}}_m$ via slicing.

6) Cancel the interference of a_m in $r^{(m)}$ to obtain the reduced-order problem by

$$r^{(M-1)} = r^{(M)} - h_M \quad (10)$$

7) If $m > 1$, let $m = m - 1$ and go back to step P2. With the corresponding $r^{(m-1)}$, a^{m-1}, H^{m-1} and F^{m-1}.

1. Simulation results

The simulation is performed using the following parameters:

TABLE I

SIMULATION PARAMETERS

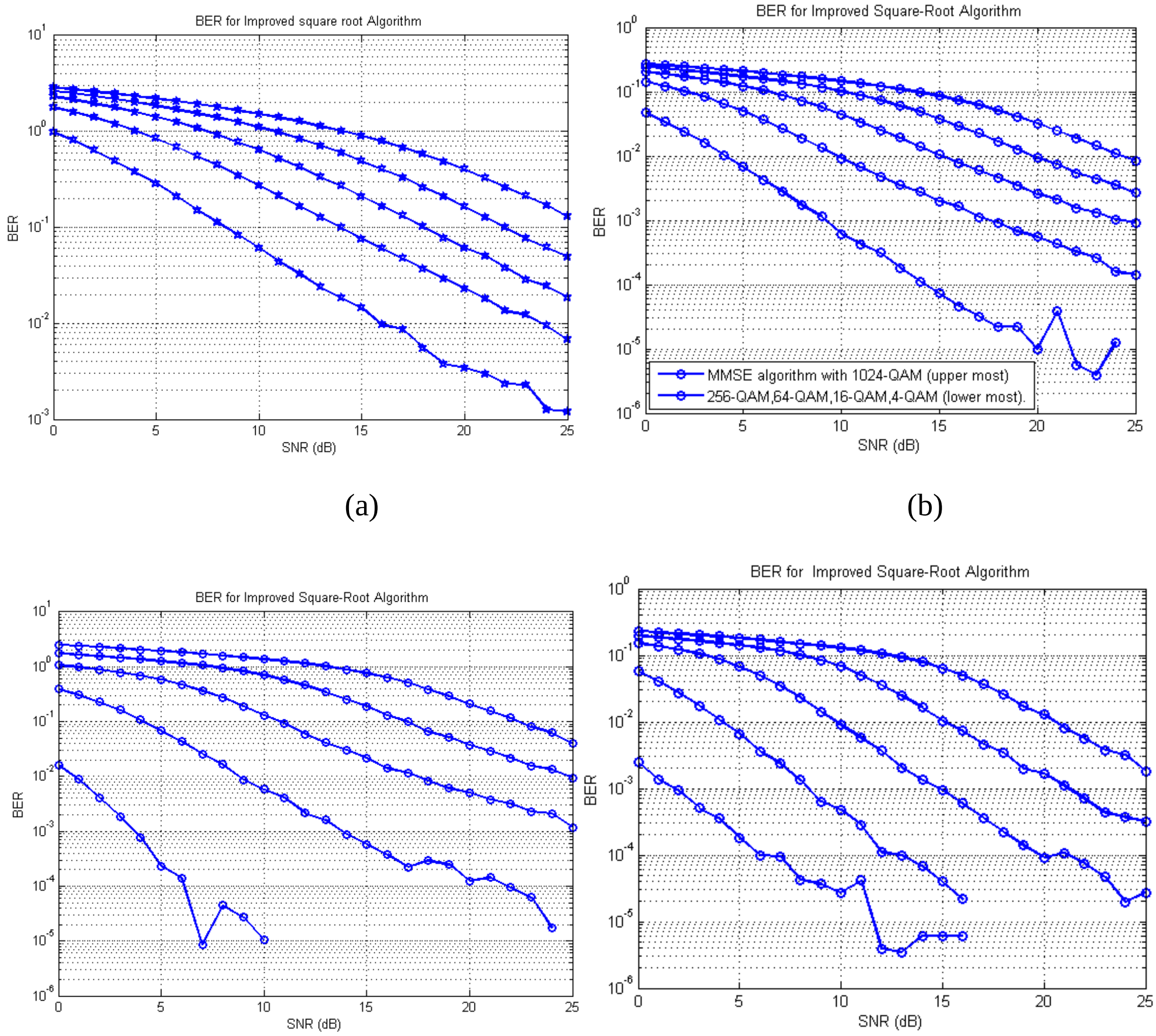
Antenna Configurations (Transmitting X Receiving)	2x2;4x4;8x8;16x16
Input Image Dimension	320x300
SNR (db)	0 to 25
Compression Applied	None
Frame Size Assumed	4
Channel Characteristics	Rayleigh Flat Fading varying randomly with every frame
Modulation and Demodulation applied	4,16,64,256,1024 QAM

From figure 2 (a),(b),(c),(d) and figure 3 (a),(b),(c),(d) we observe lower BER,SER when the Modulation scheme employed has lower constellation i.e. at lower data rates (4, 16, 64, 256 QAM), but at higher constellation i.e. at 1024 QAM Modulation higher is the BER,SER , which is independent for given antenna configuration. Optimum BER and SER can also be achieved by increasing the number of transmitting and receiving antennas. The gaps observed in the graph indicate a BER of zero i.e. the transmitted image was received without any errors.

From Figure 4 we observe the difference in the quality of the image reconstructed at the receiver compared to the original image that was transmitted. The Quality of the Image Reconstructed i.e. the PSNR is higher at lower constellation i.e. at lower data rates (4, 16, 64, 256 QAM), but at higher constellation i.e. at 1024 QAM Modulation scheme deterioration in the quality of image is observed. Improvement in PSNR is also observed when the number of transmitting and receiving antennas are increased (Figure 4(a),(b),(c),(d)). The gaps observed in the graph indicate a PSNR of infinity.

Figure 5(a) compares the Number of FLOPS required for the conventional Detection scheme employing MMSE and ZF, An Efficient Square-Root Algorithm for BLAST employing MMSE and An Improved Square Root Algorithm for BLAST employing MMSE (one complex multiplication and addition requires six and two flops respectively).since the Improved Square Root Algorithm for BLAST employs unitary transformation and utilizes intermediate results for detection the algorithm outperforms the efficient square root algorithm in terms of Number FLOPS required for detecting the received symbols. Figure 5:(b) is the original transmitted Image, Figure 5 (c),(d),(e),(f) are the Reconstructed Image at the receiver for SNR= 0,5,10,15 with An Improved square root algorithm with Minimum Mean Square Error (MMSE). The Quality of the image is directly related to the BER observed.

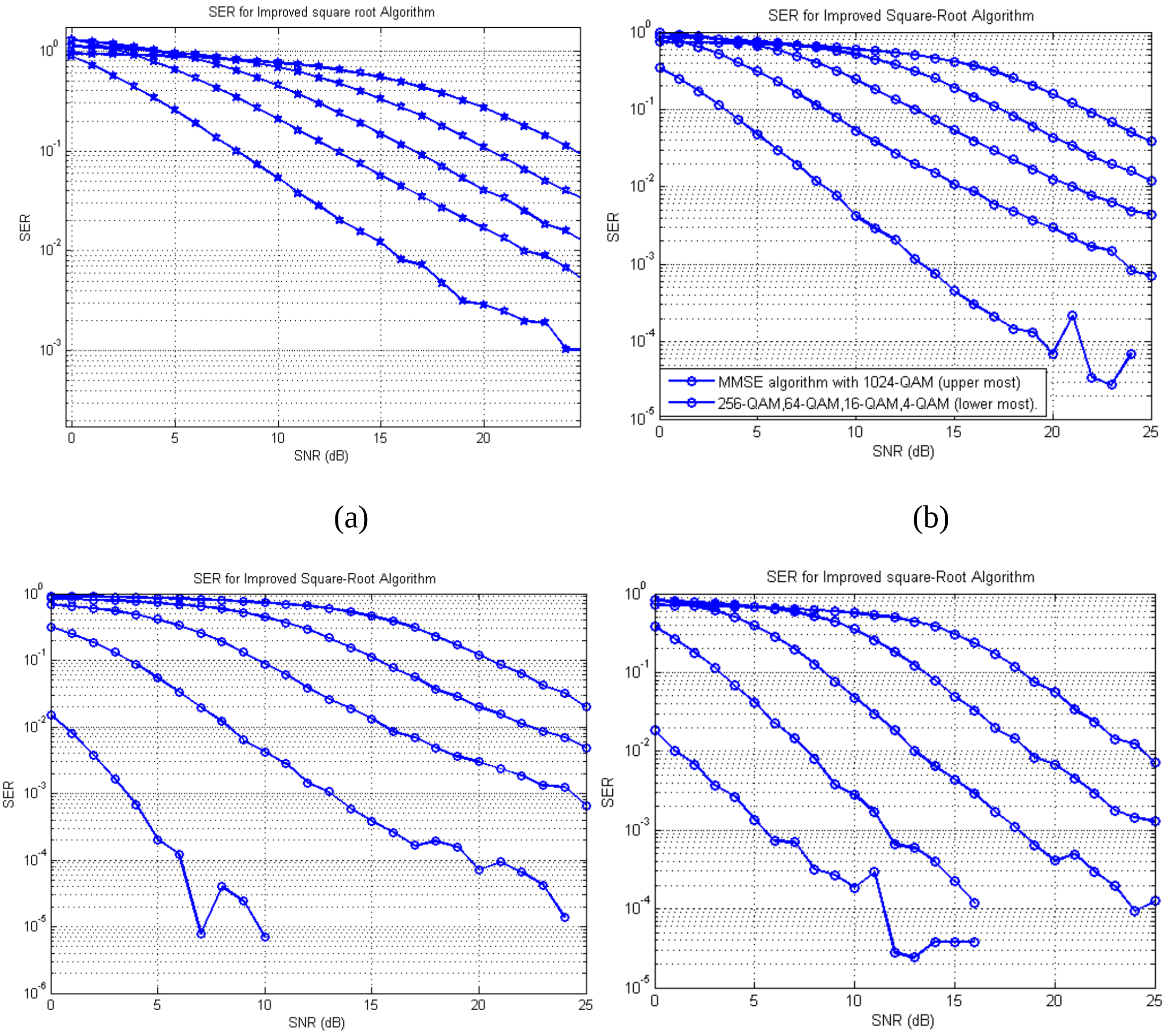
From figure 6 compares the time required for detection for conventional Detection scheme employing MMSE and ZF, An Efficient Square-Root Algorithm for BLAST employing MMSE and An Improved Square Root Algorithm for BLAST employing MMSE. The Time required is directly related to the Number of flops required for execution, as the number of transmitting and receiving antennas are increased an increase in time require for detection is observed as in figure 6 (a),(b),(c),(d) .



(a) (b)

(c) (d)

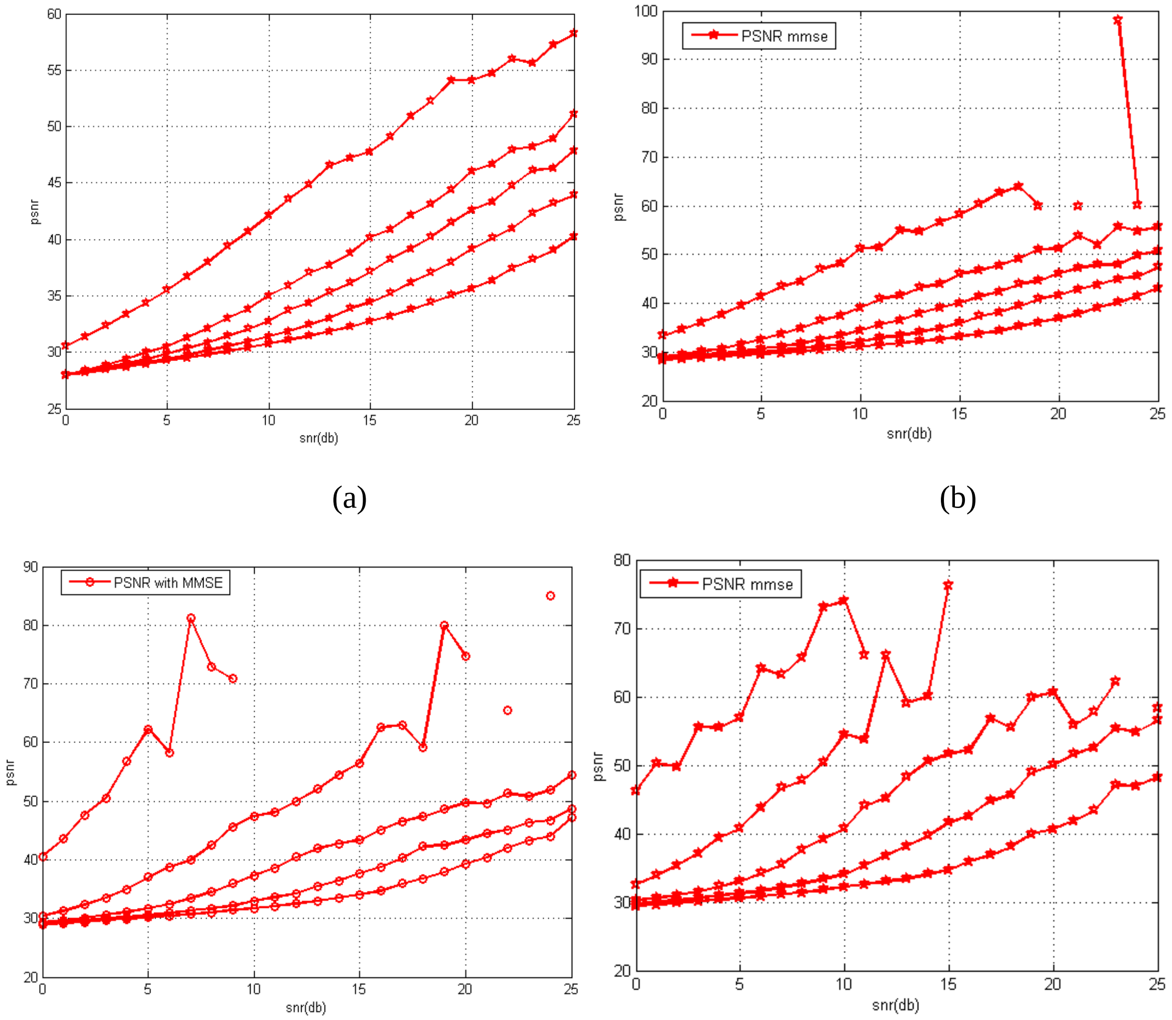
Figure 2: BER obtained for An Improved square root algorithm with Minimum Mean Square Error (MMSE) (a) BER observed for an 2x2 antenna configuration (b) BER for 4x4 antenna configuration (c) BER for 8x8 antenna configuration (d) BER for 16x16 antenna configuration. (In the ascending order, 1st (Lower most) blue line, 2nd blue line, 3rd blue line, 4th blue line, 5th (upper most) blue line indicate BER observed employing An Improved square root algorithm with MMSE detection scheme with 4-QAM modulation,16-QAM modulation,64-QAM modulation, 256-QAM modulation and 1024-QAM modulation respectively)



(a) (b)

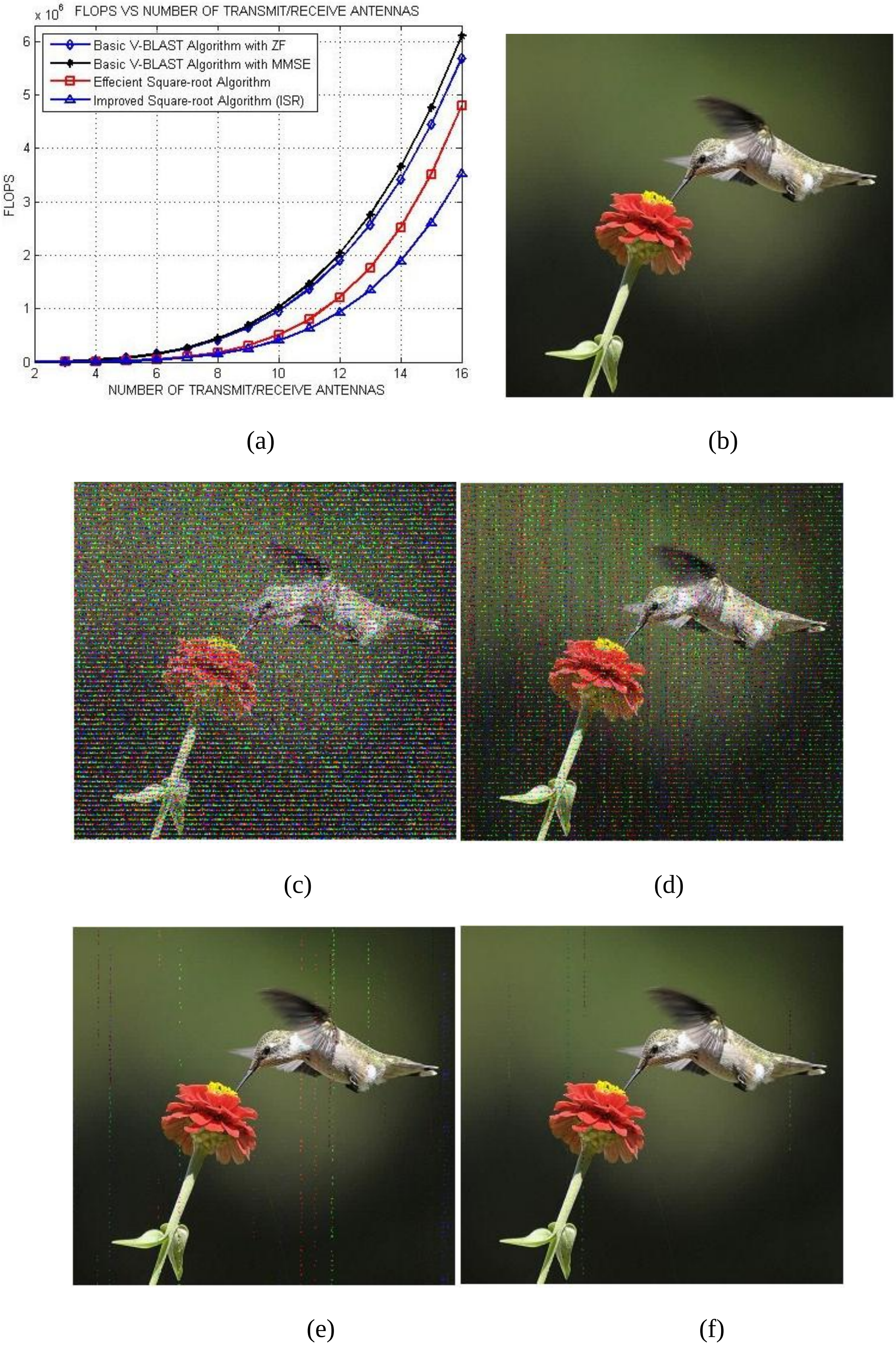
(c) (d)

Figure 3: SER obtained for An Improved square root algorithm with Minimum Mean Square Error (MMSE) (a) SER observed for an 2x2 antenna configuration (b) SER for 4x4 antenna configuration (c) SER for 8x8 antenna configuration (d) SER for 16x16 antenna configuration. (In the ascending order, 1st (Lower most) blue line, 2nd blue line, 3rd blue line, 4th blue line, 5th (upper most) blue line indicate SER observed employing An Improved square root algorithm with MMSE detection scheme with 4-QAM modulation,16-QAM modulation,64-QAM modulation, 256-QAM modulation and 1024-QAM modulation respectively)



(a) (b) (c) (d)

Figure 4: PSNR Comparison between the Reconstructed Output and the Original Image Transmitted For An Improved square root algorithm with Minimum Mean Square Error (MMSE) (a) PSNR observed for an 2x2 antenna configuration (b) PSNR for 4x4 antenna configuration (c) PSNR for 8x8 antenna configuration (d) PSNR for 16x16 antenna configuration.(In the ascending order, 1st (Lower most) red line, 2nd red line, 3rd red line, 4th red line, 5th (upper most) red line indicate PSNR observed employing An Improved square root algorithm with MMSE detection scheme with 1024-QAM modulation, with 256-QAM modulation, with 64-QAM modulation, with 16-QAM modulation and with 4-QAM modulation respectively.)



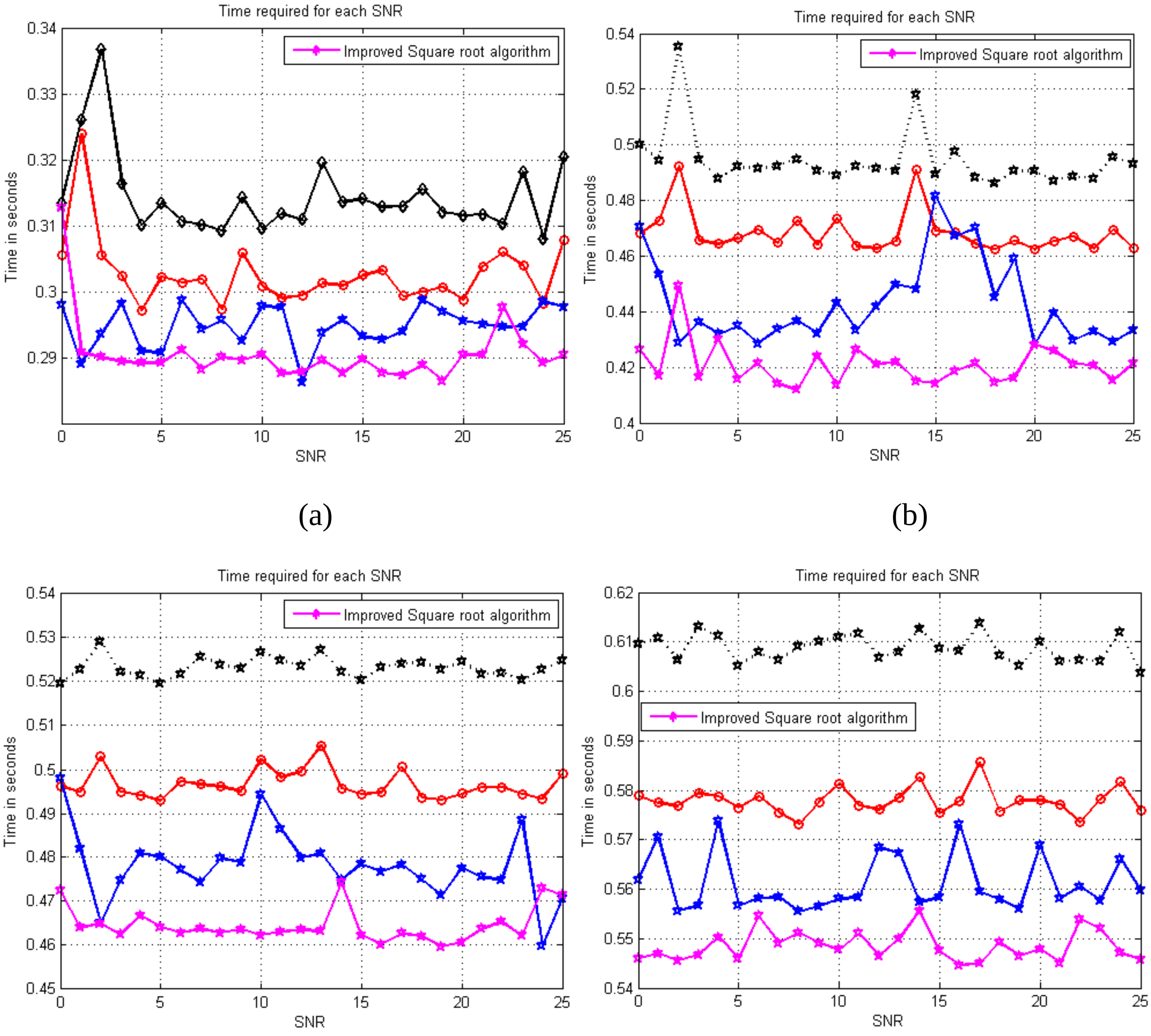
(a) (b)

(c) (d)

(e) (f)

Figure 5: (a) TOTAL FLOPS required for conventional detection with ZF and MMSE, An efficient square root algorithm and An improved square root algorithm [7] (b) Original Transmitted Image (c) Reconstructed Output

Image at SNR=0 (d) Reconstructed Output Image at SNR=5 (e) Reconstructed Output Image at SNR=10 (f) Reconstructed Output Image at SNR=15



(a) (b)

(c) (d)

Figure 6:(a) Time required for detection with 2x2 antenna configuration (b) Time required for 4x4 antenna configuration (c) Time required for 8x8 antenna configuration (d) Time required for 16x16 antenna configuration. (Black: conventional detection with MMSE; red conventional detection with ZF; blue: efficient square root algorithm employing MMSE[7]; magenta: an improved square root algorithm with MMSE)

B. *An Improved Square-Root Algorithm for V-BLAST Based on Efficient Inverse Cholesky Factorization*

Further reduction in the number of FLOPS is can achieved by employing a fast algorithm for inverse Cholesky factorization used to compute a triangular square-root of the estimation error covariance matrix, it is then applied to propose an improved square-root algorithm for V-BLAST, which speedups several steps in the previous one and can offer further computational savings in MIMO Orthogonal Frequency Division Multiplexing (OFDM) systems. Compared to the conventional inverse Cholesky factorization, the proposed one avoids the back substitution (of the Cholesky factor), and then requires only half divisions. The algorithm is faster than the existing efficient V-BLAST algorithms [12].

Initialization:

1) Set $m = M$. Compute R_M, Z_M and the initial upper triangular $F = F_M$. This step includes in the sub-steps N1-a, N1-b, N1-c and N1-d.

1-a) Assume the successive detection order to be $[t_M, t_{M-1}, \cdot\cdot\cdot, t_1]$. Correspondingly permute H to be $H = H_M = [h_{t1}, h_{t2}, \cdot\cdot\cdot, h_{tM}]$.

1-b) Utilize the permuted H to compute R_M, where we can obtain all R_{m-1}s, v_{m-1}s and β_ms (for $m = M$, M -1, · · · , 2), as shown

$$R_m = \begin{bmatrix} R_{m-1} & v_{m-1} \\ v_{m-1}^H & \beta_m \end{bmatrix}$$

(11)

Where $R = H^H H + \alpha I_M$.

1-c) Compute F_1 by $F_1 = \sqrt{R_1^{-1}}$ Then use

$$\lambda_m = 1/\sqrt{\beta_m - v_{m-1}^H F_{m-1} F_{m-1}^H v_{m-1}}$$

$u_{m-1} = -\lambda_m F_{m-1} F_{m-1}^H v_{m-1}$ and

$$F_m = \begin{bmatrix} F_{m-1} & u_{m-1} \\ 0_M^T & \lambda_m \end{bmatrix} \quad (12)$$

To compute F_m from F_{m-1} iteratively for $m = 2, 3, \cdot\cdot\cdot$, to obtain the Initial $F = F_M$.

1-d) Compute $z_M = H_M^H x^{(M)} = H_M^H$ x. (13)

Iterative Detection:

2) Find the minimum length row in F_m and permute it to be the last *m-th* row. Correspondingly permute z_m, and rows and columns in R.

3) Block upper-triangularize F_m by

$$F_m \Sigma = \begin{bmatrix} F_{m-1} & u_{m-1} \\ 0_M^T & \lambda_m \end{bmatrix} \quad (14)$$

Where Σ is a unitary transformation, u_{m-1} is an $(m-1) \times 1$ column vector, and λ_m is a scalar.

4) Form the least-mean-square estimate $\hat{a}_m$ by

$$\hat{a}_m = \lambda_m [(u_{m-1}) (\lambda_m)^*] z_m \qquad (15)$$

5) Obtain a_m from $\hat{a}_m$ via slicing

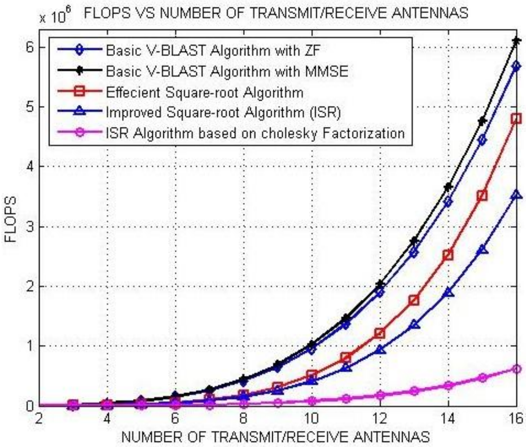
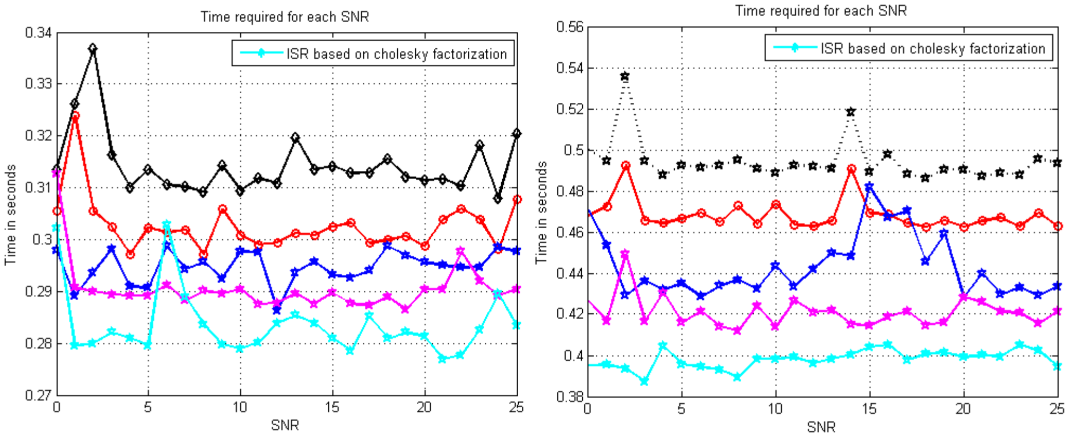
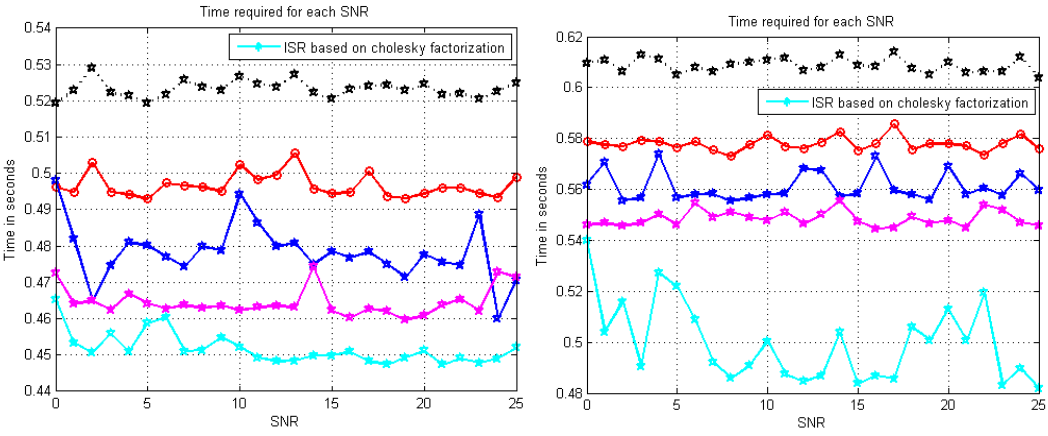


Figure 7: TOTAL FLOPS required for conventional detection scheme with ZF and MMSE, an efficient square root algorithm employing MMSE[7], an improved square root algorithm with MMSE and an improved square root algorithm based on cholesky factorization with MMSE.



(a) (b)



(c) (d)

Figure 8:(a) Time required for detection for 2x2 antenna configuration (b) Time required for 4x4 antenna configuration (c) Time required for 8x8 antenna configuration (d) Time required for 16x16 antenna configuration. (Black: conventional detection with MMSE; red conventional detection with ZF; blue: efficient square root algorithm employing MMSE[7]; magenta: an improved square root algorithm with MMSE and cyan: an improved square root algorithm based on cholesky factorization with MMSE)

6) Cancel the effect of a_m in z_m by

$$z_{m-1} = z_m^{[-1]} - a_m v_{m-1} \qquad (16)$$

Where $z_m^{[-1]}$ is the permuted z_m with the last entry removed, and v_{m-1} is in the permuted R_m

7) If $m > 1$, let $m = m - 1$ and go back to step N2 with the corresponding z_{m-1}, a_{m-1}, R_{m-1} and F_{m-1}.

1. Simulation results

Simulation is performed using the parameters from Table I. The performance parameters such as BER, SER and PSNR are similar to the results obtained for An Improved Square Root Algorithm for V-BLAST employing MMSE.

Figure 7 compares the Number of FLOPS required for the conventional Detection scheme employing MMSE and ZF, An Efficient Square-Root Algorithm for V-BLAST employing MMSE, An Improved Square Root Algorithm for V-BLAST employing MMSE and An Improved Square-Root Algorithm for V-BLAST Based on Efficient Inverse Cholesky Factorization employing MMSE (one complex multiplication and addition require six and two flops respectively).An Improved Square-Root Algorithm for V- BLAST Based on Efficient Inverse Cholesky Factorization outperforms all the above mentioned Algorithms and is faster than the existing efficient V-BLAST algorithms.

Figure 8 compares the time required for detection between conventional detection employing ZF, MMSE and an efficient square root algorithm employing MMSE, An Improved Square Root Algorithm for V-BLAST employing MMSE and An Improved Square-Root Algorithm for V-BLAST Based on Efficient Inverse Cholesky Factorization employing MMSE. Due to the achieved reduction in the Number of floating point operation, reduction in the time required for detection is observed when Improved Square-Root Algorithm for V-BLAST Based on Efficient Inverse Cholesky Factorization is employed with MMSE.

IV CONCLUSION

This paper provides a performance comparison between different detection schemes employed in V-blast MIMO Wireless Communications which includes An Improved Square Root Algorithm for V-BLAST employing MMSE and An Improved Square-Root Algorithm for V-BLAST Based on Efficient Inverse Cholesky Factorization employing MMSE. Reduction in the number of FLOPS required for detection is accomplished by the improved square root algorithm which utilizes intermediate results that were discarded without any usage in the efficient square root algorithm. The number of FLOPS required for detection with improved square root algorithm employing MMSE for 16 transmitting and 16 receiving antennas is 3.5×10^6, a reduction of 1.3×10^6 FLOPS is achieved compared to the efficient square root algorithm with MMSE and reduction 2.3×10^6, 2.7×10^6 FLOPS is achieved compared to conventional detection scheme employing ZF, with MMSE respectively. Further reduction in number of FLOPS is achieved by employing a fast algorithm to compute a triangular square root of the estimation error covariance matrix. The number of FLOPS required improved square root algorithm based on efficient inverse cholesky factorization with MMSE for 16 transmitting and 16 receiving antennas is 0.6

x 10^6, a reduction of 2.9x$10^{6,}$ 4.2x10^6, 5.2x10^6 and 5.6x10^6 is achieved compared to improved square-root algorithm, the efficient square root algorithm and the conventional detection scheme employing ZF,MMSE respectively. The algorithm is faster than the existing efficient V-BLAST algorithms.

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Shankar.P received B.E in electronics and Communication from Visvesvaraya Technological University (VTU) in the year 2010, and currently pursuing M.TECH in Communication System from R.V.C.E Bangalore, Karnataka, India. His main research interests include antennas and propagation for personal communications, MIMO, radar remote sensing, numerical electro-magnetic, and optical fiber communications.

Dr Hariprasad S.A obtained his PhD from Avinashilingam University for Women, Coimbatore in the area of digital controller's .He is having teaching experience of 22 years and five years of research national journals and conferences. He has also published a text book on advanced Microprocessor and reviewed books on Microwave engineering and won best teacher award (twice) from RSST and appreciation award from ISTE. His research areas of interest are embedded systems and RF systems.