The 2014 International Conference on Advanced Technologies for Communications (ATC'14)

Low-Complexity Detectors for High-Rate Spatial Modulation

Tien-Dong Nguyen*, Xuan-Nam Tran*, Trung-Minh Do†, Vu-Duc Ngo‡, and Minh-Tuan Le§
*Le Quy Don Technical University, 100 Hoang Quoc Viet, Cau Giay, Ha Noi, Vietnam
Email: qttdong@gmail.com, namtx@mta.edu.vn
†Vietnam Mobile Telecom Services Center I, VMS I, 811A Giai Phong, Hoang Mai, Hanoi, Vietnam
E-mail: minhdt@vms.com.vn
‡School of Electronics and Telecommunications, HUST, 1 Dai Co Viet, Hanoi, Vietnam
E-mail: duc.ngovu@hust.edu.vn
§Hanoi Department of Science and Technology, 5 Nguyen Trai Str., Ha Dong, Hanoi, Vietnam
E-mail: tuan.hdost@gmail.com

***Abstract*—A High-rate Spatial Modulation (HR-SM) scheme, whose maximum spectral efficiency is in proportional to the number of transmit antennas n_T, was proposed in [1]. However, the complexity of its maximum likelihood detector grows exponentially with n_T, making it impractical as n_T increases. Based on the codeword structure of the HR-SM scheme and on the conventional successive-interference-cancellation (SIC) detectors, this paper proposes low-complexity suboptimal detectors for the HR-SM scheme. These detectors can feasibly be utilized in the HR-SM scheme with large number of transmit antennas and high-order QAM/PSK modulations. In addition, simulation results and complexity analysis are presented to verify performances and complexities of the proposed decoders.**

I. Introduction

Multiple-Input Multiple-Output (MIMO) wireless communication systems are shown to be of higher spectral efficiency than the conventional single antenna systems [2]–[3]. These systems can be classified into three main categories: 1) Space-time coding to achieve diversity gain; 2) MIMO precoding with channel state information (CSI) available at the transmitter to achieve capacity gain; and 3) Layered space time code to exploit multiplexing gain (i.e., spatial division multiplexing) [4]. However, one of the main challenges in MIMO system implementation is to reduce detection complexity while maintaining reception quality at a reasonable level.

In the literature, many suboptimal MIMO detection techniques are studied. First, the linear detectors such as zero-forcing (ZF) and minimum mean square error (MMSE) were used for signal detection in spatial division multiplexing (SDM) systems. The key advantage of these detectors is their low complexity . However, bit error rate (BER) performance provided by linear detectors is quite poor, especially when the number of transmit antennas are large. Therefore, various successive interference cancellation (SIC) detectors were devised to improve detection performance [5]–[9]. In [7], V–BLAST (Vertical Bell Labs Layered Space Time) detector was developed for signal detection in the layered space-time system. This detector, referred to as ZF-BLAST, is actually a zero-forcing (ZF) detector with ordered SIC. In this detection scheme, signal layer with the smallest mean square error (MSE) is detected first and is canceled out from the received signal vector under the assumption that the signal layer is detected without error. The procedure is repeated until the last layer is detected. In [5]–[6], other SIC detectors based on the sorted QR decomposition (SQRD) were proposed for the detection of the layered space-time sytem. It was shown that the SQRD required less computational complexity in comparison with the V-BLAST with only a small degradation in error performance. In [8] and [9], an MMSE detector with order SIC, called MMSE-BLAST, and an MMSE-SQRD were respectively presented for the detection of the BLAST system. It was demonstrated that by taking the noise variance into consideration, MMSE-BLAST offered the lowest bit error rate (BER) among SIC-based detectors, followed by the MMSE-SQRD [9]. Nonetheless, MMSE-BLAST has high computational complexity due to the repeated pseudo matrix inversion.

The HR-SM system proposed in [1] provides a substantial increase in spectrum efficiency compared to the spatial modulation (SM) scheme in [14] and the GSM in [15]–[16]. The additional benefit is that the HR-SM codewords are easily designed. At the receiver, transmitted HR-SM codewords are optimally detected by using the maximum–likelihood (ML) detection technique. However, this detection method could hardly be deployed in practice because its complexity grows exponentially with the number of transmit antennas. Evidently, it is desirable to apply other detection approaches to reduce complexity at the receiver of the HR-SM scheme. In fact, several sub-optimal detectors have been proposed for signal detection in SM systems, such as the iMRC detector in [14] or the sphere decoder in [22]. These decoders, however, cannot be applied to the HR-SM in their original forms.

In this paper, by exploiting codeword structure of the HR-SM scheme and based on the conventional MMSE-VBLAST and MMSE-SQRD detectors, we propose low–complexity sub–optimal detectors for the HR-SM systems. Analysis and simulation results show that the proposed detectors remarkably reduce computational complexity as compared to the optimal ML detector in [1], particularly when the number of transmit antennas is large. Nonetheless, the reduction in detection

978-1-4799-6956-2/14/$31.00 ©2014 IEEE

complexity is achieved at the cost of performance degradation.

The remainder of the paper is organized as follows. In section II, the HR-SM scheme is briefly described. Section III presents the proposed detectors. The complexity analsysis and the performance comparison are given in section IV and V, respectively. The last section concludes this paper.

II. System Model

Let us consider a HR-SM system with n_T transmit and n_R receive antennas in the presence of a quasi-static Rayleigh fading MIMO channel, as illustrated in Fig. 1. During a symbol period, $l+m$ data bits are fed into the HR-SM transmitter. Where l bits are mapped into a SC codeword $\mathbf{s}$, out of K SC codewords within the spatial constellation Ω_s, the remaining m bits are modulated using a M-QAM or M-PSK modulator to get modulated symbol x. As proposed in [1], the SC codeword $\mathbf{s}$ is designed by fixing the first entries of $\mathbf{s}$ with 1 and assigning the remaining entries with values randomly selected from the set $\{\pm 1, \pm j\}$, where $j^2 = -1$. Therefore, there are a total of $K = 4^{(n_T - 1)}$ SC codewords in Ω_s. An $n_T \times 1$ HR-SM codeword $\mathbf{c}$ is created simply by multiplying $\mathbf{s}$ and x , i.e., $\mathbf{c} = \mathbf{s}x$. Then, the codeword is transmitted via n_T antennas within a symbol period.

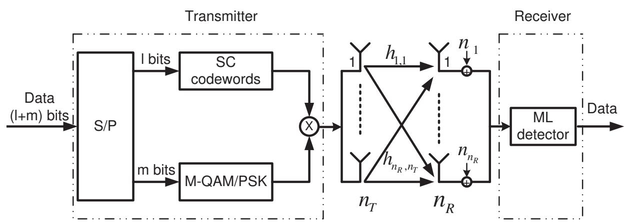

Fig. 1. Block diagram of a HR-SM system

At the receiver, the $n_R \times 1$ receive signal vector $\mathbf{y}$ is given by:

$$\mathbf{y} = \sqrt{\frac{\gamma}{n_T E_s}}\mathbf{H}\mathbf{c} + \mathbf{n} \tag{1}$$

$$= \sqrt{\frac{\gamma}{n_T E_s}}\mathbf{H}\mathbf{s}x + \mathbf{n} \tag{2}$$

where $\mathbf{H}$ and $\mathbf{n}$ respectively denote $n_R \times n_T$ channel matrix and $n_R \times 1$ noise vector. The entries of $\mathbf{H}$ and $\mathbf{n}$ are assumed to be independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance. E_s is the average symbol energy of x. γ is the average SNR at each receive antenna.

The spatial constellation (SC) codeword $\mathbf{s}$ and modulated symbol x are jointly detected at the receiver by using the ML detector [1] under the assumption that CSI is perfectly known by the receiver. This, however, will lead to a noticeable increase in detection complexity.

III. Proposed Detectors

In this section, we proposed sub-optimal detectors based on the conventional SIC ones for signal detection in the HR-SM system in order to reduce detection complexity.

TABLE I
MBLAST Detection Algorithm

Input:	$\mathbf{y}$, $\tilde{\mathbf{H}}$, E_s
Output:	$\hat{x}, \hat{\mathbf{c}}$

1. Compute $\mathbf{P} = \left(\tilde{\mathbf{H}}\tilde{\mathbf{H}}^H + \frac{1}{E_s}\mathbf{I}_{n_T}\right)^{-1}$.
2. Find the strongest signal index based on $k = \arg\min_j \mathbf{P}_{j,j}$, where $\mathbf{P}_{j,j}$ is the j diagonal entry of $\mathbf{P}$, and reorder the entries of $\mathbf{c}$ so that the smallest diagonal entry is the first one.
3. Compute the MMSE filter matrix $\mathbf{G}_{MMSE}$ as in (4) and form the LMS estimate $\tilde{c}_k = \mathbf{g}_{MMSE,k}\mathbf{y}$, where $\mathbf{g}_{MMSE,k}$ is the kth row of $\mathbf{G}_{MMSE}$.
4. Obtain $\hat{c}_k$ by slicing $\tilde{c}_k$.
5. Cancel the effect of $\hat{c}_k$ from $\mathbf{y}$ and re-organize the channel matrix $\tilde{\mathbf{H}}$ by deleting its kth column.
6. Repeat Steps 2 to 6 until all entries of $\mathbf{c}$ are detected.
7. Re-arrange the entries of $\hat{\mathbf{c}}$ in the same order as they are transmitted.
8. Get the recovered modulated symbol and SC codewords as $\hat{x} = \hat{c}_1$ and $\hat{\mathbf{s}} = \frac{\hat{\mathbf{c}}}{\hat{x}}$.

A. Modified MMSE-BLAST and Modified MMSE-SQRD Detectors

First, the HR-SM codeword $\mathbf{c}$ can be explicitly expressed as:

$$\begin{aligned}\mathbf{c} &= \begin{bmatrix} c_1 & c_2 & \cdots & c_{n_T} \end{bmatrix}^T \\ &= \begin{bmatrix} x & s_2 x & \cdots & s_{n_T} x \end{bmatrix}^T \end{aligned} \tag{3}$$

where T denotes matrix transpose.

Since $s_i \in \{\pm 1, \pm j\}$, $i = 2, 3, \cdots, n_T$, while x belongs to a M-QAM/PSK constellation, it follows that $c_k, k = 1, 2, \cdots, n_T$, also belongs to the same constellation as x[1]. This means that conventional SIC detectors can be applied to (1) to detect c_k. From (3) we can see that after getting the recovered signal vector $\hat{\mathbf{c}}$, we are able to get the recovered modulated symbol and SC codewords as $\hat{x} = \hat{c}_1$ and $\hat{\mathbf{s}} = \frac{\hat{\mathbf{c}}}{\hat{x}}$.

1) Modified MMSE-BLAST detector: Consider the HR-SM system as an SDM system, the MMSE filter matrix at the receiver can be computed as follows:

$$\mathbf{G}_{MMSE} = \tilde{\mathbf{H}}^H\left(\tilde{\mathbf{H}}\tilde{\mathbf{H}}^H + \frac{1}{E_s}\mathbf{I}_{n_T}\right)^{-1} \tag{4}$$

where $\tilde{\mathbf{H}} = \sqrt{\frac{\gamma}{n_T E_s}}\mathbf{H}$ and $\mathbf{I}_{n_T}$ is the $n_T \times n_T$ identity matrix.

In order to obtain high performance, MMSE-BLAST detector finds the strongest signal, in terms of the smallest MSE, slices its least-mean-squares (LMS) estimate to the nearest value in the signal constellation, and cancels the effect of the sliced signal from the received signal vector $\mathbf{y}$. The detection procedure repeats in the same manner until all the signals are detected [8].

The modified MMSE-BLAST (MBLAST) detection algorithm can be summarized as in Table I.

[1]This statement is true if the QAM constellations are square ones, i.e., $M = 2^{2n}$ for some non-negative integer n.

TABLE II
MSQRD DETECTION ALGORITHM

Input: $\mathbf{z}$, $\mathbf{D}$
Output: $\hat{x}, \hat{\mathbf{c}}$

1. Decompose $\mathbf{D}$ using MMSE-SQRD algorithm to get $\mathbf{Q}$, $\mathbf{R}$, and the permutation vector $\mathbf{p}$.
2. Compute $\mathbf{v} = \mathbf{Q}^H \mathbf{z}$.
3. Detection and Cancellation:
   for $k = n_T : -1 : 1$
      if $k == n_T$
         Obtain $\hat{c}_k$ by slicing $v_k / r_{k,k}$.
      else
         for $l = k+1 : n_T$
            $v_k = v_k - r_{k,l}\hat{c}_l$
         end
         Obtain $\hat{c}_k$ by slicing $v_k / r_{k,k}$.
      end
   end
4. Re-arrange the entries of the recovered codeword $\hat{\mathbf{c}}$ in the same order as they are transmitted using the permutation vector $\mathbf{p}$.
5. Get the recovered modulated symbol and SC codewords as $\hat{x} = \hat{c}_1$ and $\hat{\mathbf{s}} = \frac{\hat{\mathbf{c}}}{\hat{x}}$.

2) Modified MMSE-SQRD detector: The MVBLAST detector needs to do matrix inversion repeatedly. As a result, its computational load is high, particularly when the number of deployed antennas increases. To overcome this problem, we utilize the MMSE-SQRD in [9] to recover transmitted signals.

Let us define a $(n_T + n_R) \times n_T$ extended channel matrix $\mathbf{D}$ and a extended received vector $\mathbf{z}$ as follows:

$$\mathbf{D} = \begin{bmatrix} \tilde{\mathbf{H}} \\ \frac{1}{\sqrt{E_s}} \mathbf{I}_{n_T} \end{bmatrix}, \quad \mathbf{z} = \begin{bmatrix} \mathbf{y} \\ \mathbf{0} \end{bmatrix} \tag{5}$$

Applying the MMSE-SQRD to decompose $\mathbf{D}$, we have:

$$\mathbf{D} = \mathbf{QR} \tag{6}$$

where $\mathbf{Q}$ is a $(n_T + n_R) \times n_T$ matrix with orthonormal columns, i.e., $\mathbf{Q}^H\mathbf{Q} = \mathbf{I}_{n_T}$, and $\mathbf{R}$ is an $n_T \times n_T$ upper triangular matrix.

Multiplying $\mathbf{z}$ by $\mathbf{Q}^H$, we get:

$$\begin{aligned} \mathbf{v} &= \mathbf{Q}^H \mathbf{z} \\ &= \mathbf{Rc} + \mathbf{w} \end{aligned} \tag{7}$$

Due to the structure of $\mathbf{R}$, the last element of $\mathbf{v}$, i.e., v_{n_T}, is a function of only c_{n_T} without being interfered by other signals. Thus, $\hat{c}_{n_T}$ can be immediately estimated by slicing $v_{n_T}/r_{n_T,n_T}$. Assuming that $\hat{c}_{n_T}$ is detected correctly, it will be cancelled out from v_{n_T-1}. v_{n_T-1} is again a function of only c_{n_T-1}. Hence, $\hat{c}_{n_T-1}$ can be immediately estimated by slicing $v_{n_T-1}/r_{n_T-1,n_T-1}$. Similarly, $\hat{c}_{n_T-1}$ and $\hat{c}_{n_T}$ will be cancelled out from v_{n_T-2} to detect $\hat{c}_{n_T-2}$. The procedure continues until $\hat{c}_1$ is obtained.

The modified MMSE-SQRD (MSQRD) detection algorithm can be summarized as in Table II.

B. Improved MMSE-SQRD Detector

First, equation (1) can equivalently be re-written as follows:

$$\mathbf{t}_x = \bar{\mathbf{H}}\bar{\mathbf{c}} + \mathbf{n} \tag{8}$$

TABLE III
ISQRD DETECTION ALGORITHM

Input: $\mathbf{y}$, $\tilde{\mathbf{H}}$
Output: $\hat{x}, \hat{\mathbf{c}}$

1. Decompose $\bar{\mathbf{H}}$ using MMSE-SQRD algorithm to get $\mathbf{Q}$, $\mathbf{R}$, and the permutation vector $\mathbf{p}$.
2. Detection and Cancellation:
   for $m = 1 : M$
      Compute $\mathbf{t}_m = \mathbf{y} - \tilde{\mathbf{h}}_1 x_m$ and $\mathbf{v} = \mathbf{Q}^H \begin{bmatrix} \mathbf{t}_m \\ \mathbf{0} \end{bmatrix}$
      for $k = n_T - 1 : -1 : 1$
         if $k == n_T - 1$
            Obtain $\hat{\bar{c}}_{m,k}$ by slicing $v_k / r_{k,k}$.
         else
            for $l = k+1 : n_T - 1$
               $v_k = v_k - r_{k,l}\hat{\bar{c}}_{m,l}$
            end
            Obtain $\hat{\bar{c}}_{m,k}$ by slicing $v_k / r_{k,k}$.
         end
      end
      Compute $d_m = \left\| \mathbf{t}_m - \bar{\mathbf{H}}\hat{\bar{\mathbf{c}}}_{m,\mathbf{p}} \right\|^2$
   end
3. Find $\hat{m}$: $\hat{m} = \arg\min_m d_m$
4. Obtain the recovered modulated symbol $\hat{x} = x_{\hat{m}}$ and the recovered SC codeword $\hat{\mathbf{s}} = \frac{1}{\hat{x}} \begin{bmatrix} \hat{x} & \hat{\bar{\mathbf{c}}}_{\hat{m},\mathbf{p}} \end{bmatrix}^T$.

where $\mathbf{t} = \mathbf{y} - \tilde{\mathbf{h}}_1 x$, $\bar{\mathbf{H}} = \begin{bmatrix} \tilde{\mathbf{h}}_2 & \tilde{\mathbf{h}}_3 & \cdots & \tilde{\mathbf{h}}_{n_T} \end{bmatrix}$ is the $n_R \times (n_T - 1)$ equivalent channel matrix, $\tilde{\mathbf{h}}_k, k = 1, 2, \cdots, n_T$, is the kth column of the channel matrix $\tilde{\mathbf{H}}$, and $\bar{\mathbf{c}}$ is the $(n_T - 1) \times 1$ new transmitted codeword consisting of the last $(n_T - 1)$ entries of $\mathbf{c}$. Clearly, for a given $x_m, m = 1, 2, \cdots, M$, in the transmitted constellation, we have a corresponding system similar to that in equation (1). Therefore, we can apply the MSQRD above to (8) to recover $\hat{\bar{\mathbf{c}}}_m$ and the corresponding Euclidean distance $d_m = \left\| \mathbf{t}_m - \bar{\mathbf{H}}\hat{\bar{\mathbf{c}}}_{m,\mathbf{p}} \right\|^2$, where $\mathbf{t}_m = \mathbf{y} - \tilde{\mathbf{h}}_1 x_m$ and $\hat{\bar{\mathbf{c}}}_{m,\mathbf{p}}$ is the vector $\hat{\bar{\mathbf{c}}}_m$ re-arranged by using permutation vector $\mathbf{p}$. The index m of transmitted symbol x is determined using $\hat{m} = \arg\min_m d_m$. Then, the transmitted symbol and the transmitted SC codeword are respectively recovered using $\hat{x} = x_{\hat{m}}$ and $\hat{\mathbf{s}} = \frac{1}{\hat{x}} \begin{bmatrix} \hat{x} & \hat{\bar{\mathbf{c}}}_{\hat{m},\mathbf{p}} \end{bmatrix}^T$. The Improved-MMSE-SQRD (ISQRD) algorithm is summarized in Table III.

IV. Complexity Analysis

In this section, complexities of the proposed detectors are analyzed. Note that performance analysis of the proposed sub-optimal decoders in comparison with the optimal one is beyond the scope of this paper and will be our future work. It assumed that a complex multiplication is equal four real multiplications and two real additions, while a complex addition is equal two real additions. A complex division is composed of eight real multiplications and three real additions. A real addition, a real division, or a real multiplication is considered a floating point operation (flop).

First, it is straightforward to show that total complexity of the ML detector (in flops) for the HR-SM scheme in [1] is equal to:

$$f_{ML} = MK\left(16n_R + 6\right) + \left(8n_R n_T - 2n_R\right)K, \tag{9}$$

where $K = 4^{n_T - 1}$.

Based on the complexity analysis in [8], complexity of the MVBLAST detector, when applied to the HR-SM system, could be shown to be equal to:

$$f_{MBLAST} = \frac{15}{4} n_T^4 + 2n_T^3 n_R + n_T^2 n_R^2 + n_T (16n_R - 2) . \quad (10)$$

The complexities of the MSQRD and the ISQRD are respectively given by:

$$f_{MSQRD} = 8n_T^3 + (8n_R - 3) n_T^2 - (10n_R + 13) n_T + 8, \quad (11)$$

and

$$\begin{aligned} f_{ISQRD} &= 8(n_T - 1)^3 + (8n_R - 11 + 12M)(n_T - 1)^2 \\ &+ (M(16n_R - 12) - 14n_R + 4)(n_T - 1) \\ &+ M(10n_R + 7) + 5. \end{aligned} \quad (12)$$

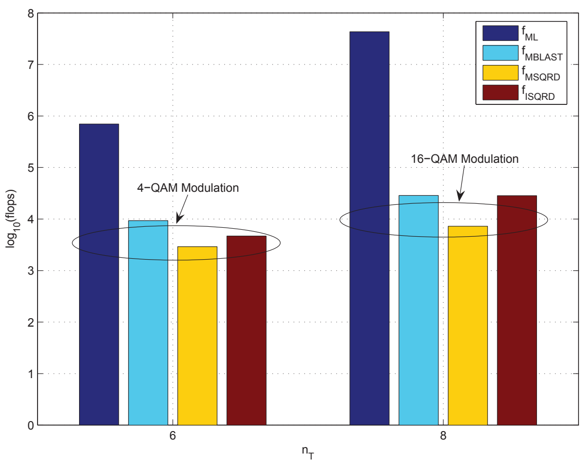

Fig. 2. Complexities of ML,MBLAST, MSQRD, and ISQRD detectors in different MIMO configurations; 4-QAM and 16-QAM modulation.

Fig. 2 illustrates the required flops for the MBLAST, MSQRD, and ISQRD detectors for two HR-SM systems. The first system, referred to as the (6, 6) system, is equipped with $n_R = n_T = 6$ and uses 4-QAM modulation. The second one, referred to as the (8, 8) system, is equipped with $n_R = n_T = 8$ and uses 16-QAM modulation. It can be clearly seen from the Fig. 2 that in both cases, the ML detector has significantly higher complexity than the remaining ones. Among the suboptimal detectors, the MSQRD always has the lowest complexity. Although the ISQRD has lower complexity that the MBLAST in the (6, 6) system, its complexity becomes nearly identical to that of the MBLAST in the (8, 8) system. This is due to the fact that complexity of the ISQRD depends on the modulation order M, which is increased from 4 in the (6, 6) system to 16 in the (8, 8) system.

V. Performance Comparison

In this section, we use Monte Carlo simulations to compare bit error rate (BER) performances of the proposed detectors with the existing ML one when they are used for signal recovery in a HR-SM scheme. We assume the channel state information is perfectly known by the receiver.

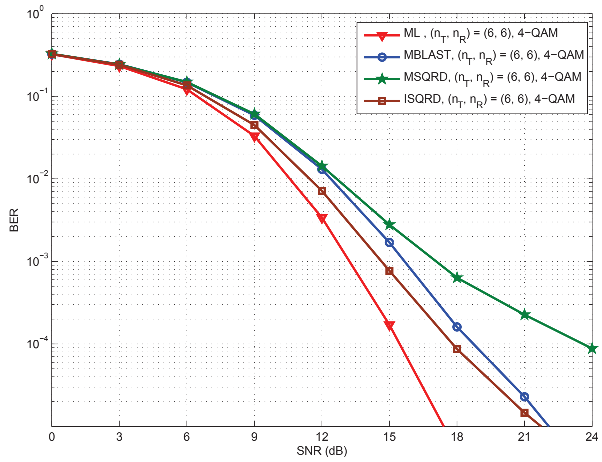

Fig. 3. BERs of a HR-SM scheme with $n_T = n_R = 6$ when using the ML, MBLAST, MSQRD, and ISQRD detectors; 4-QAM modulation.

Shown in Fig. 3 are the bit error rate (BER) curves of a HR-SM system with $n_T = 6$ transmit and $n_R = 6$ receive antennas and 4-QAM modulation as the ML, MBLAST, MSQRD, and ISQRD detectors are utilized.

From analytical and simulation results in Fig. 2 and Fig. 3, one can see that although the ML detector has the highest BER performance, its complexity is also very high, thus preventing it from practical deployment. On the other hand, in spite of the fact that the MSQRD offers the lowest detection complexity, it suffers from significant performance degradation. For example, at BER = 10^{-4}, the MSQRD losses about 8.5 dB, 5.5 dB, and 4.8 dB as compared to the ML, ISQRD and MBLAST, respectively. The SNR losses get larger as smaller BER is required. Using the MBLAST and ISQRD detectors enables the HR-SM scheme to reduce performance losses remarkably compared to the optimal performance, with the corresponding SNR losses of around 4.5 dB and 4 dB at BER = 10^{-5}, while lowering detection complexity substantially. Specifically, from Fig. 2, when $n_T = n_R = 6$, using the MBLAST and ISQRD can reduce complexity by approximately 75 times and 149 times, respectively, compared to using the ML detector. It is also worth noting that in the (6, 6) system, the ISQRD achieves both higher performance and lower complexity than the MBLAST.

When $n_T = n_R = 8$ and 16-QAM modulation are deployed, using the MBLAST and ISQRD can reduce complexity by about 1509 times and 1523 times, respectively, compared to using the ML detector. However, huge amounts of computational savings are obtained at the cost of more than 9 dB performance degradation at BER = 10^{-5}, as demonstrated in Fig. 4. It can also be seen from Fig. 2 and Fig. 4 that for nearly the same complexity, the ISQRD has remarkably higher

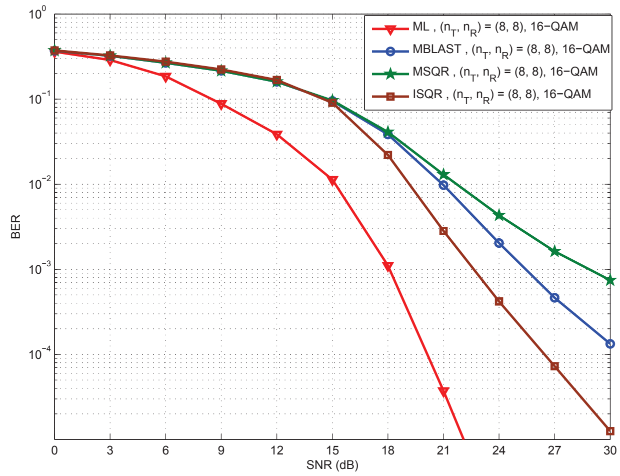

Fig. 4. BERs of a HR-SM scheme with $n_T = n_R = 8$ when using the ML, MBLAST, MSQRD, and ISQRD detectors; 16-QAM modulation.

performance than the MBLAST, particularly in the high SNR region. In addition, the MBLAST tends to make the diversity order of the HR-SM system reduce more seriously than the ISQRD as SNR increases.

VI. Conclusion

In this paper, we present the modified versions of the conventional MMSE-BLAST and MMSE-SQRD detectors, called MBLAST and MSQRD detectors, which could be used for signal detection in HR-SM systems. We also propose a new sub-optimal detector, called ISQRD, for the HR-SM systems. Analytical and simulation results show that the proposed detector achieves significant complexity reduction, yet at the cost of performance degradation, as compared to its ML counterpart. Among the sub-optimal detectors, ISQRD provides not only complexity reduction but also high BER performance. Therefore, it is a potential candidate for signal detection in the HR-SM systems with large number of transmit antennas.

References

[1] Thu-Phuong Nguyen, Minh-Tuan Le, Vu-Duc Ngo, Xuan-Nam Tran, and Hae-Wook Choi, "Spatial Modulation for High-Rate Transmission Systems," *The 79th IEEE Vehicular Technology Conference*, Seoul 2014.

[2] G. J. Foschini and M. J. Gans, "On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas," *Wireless Personal Communications*, vol. 6, pp. 311-335, 1998/03/01 1998.

[3] E. Telatar, "Capacity of Multi-antenna Gaussian Channels," *European Transactions on Telecommunications*, vol. 10, pp. 585-595, 1999.

[4] R. Y. Mesleh, H. Haas, S. Sinanovic, A. Chang Wook, and Y. Sangboh, "Spatial Modulation," *IEEE Trans. on Vehicular Techno.*, vol. 57, pp. 2228-2241, 2008.

[5] D. Wübben, J. Rinas, V. Kühn, and K. D. Kammeyer, "Efficient algorithm for decoding Layered Space-Time Codes," in *Proc. ITG Conference on Source and Channel Coding*, Berlin, Germany, January 2002.

[6] D. Wübben, R. Böhnke, V. Kühn, and K. D. Kammeyer, "Near-maximum-likelihood detection of MIMO systems using MMSE-based lattice reduction," in *Proc. IEEE International Conference on Commun.*, vol.2., pp. 798-802, 2004.

[7] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. Valenzuela, "V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel," in *Proc. URSI International Symposium on Signals, Systems, and Electronics*, pp. 295-300, 1998.

[8] B. Hassibi, "An efficient square-root algorithm for BLAST," in *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol.2, pp. II737-II740, 2000.

[9] D. Wübben, R. Böhnke, V. Kühn, and K. D. Kammeyer, "MMSE extension of V-BLAST based on sorted QR decomposition," in *Proc. Vehicular Technology Conference, VTC 2003-Fall,* vol. 1, pp. 508-512, 2003.

[10] E.Viterbo and J.Boutros, "A universal lattice code decoder for fading channel," *IEEE Trans. Inf. Theory*, vol. 45, pp. 16391642, Jul. 1999.

[11] M. O. Damen, H. El-Gamal, and G. Caire, "On maximum-likelihood detection and the search for the closest lattice point," *IEEE Trans. Inf. Theory*, vol. 49, pp. 2389-2402, 2003.

[12] Z. Wanlun and G. B. Giannakis, "Sphere decoding algorithms with improved radius search," *IEEE Trans. Commun.*, vol. 53, pp. 1104-1109, 2005.

[13] S. Byonghyo and I. Kang, "Sphere Decoding With a Probabilistic Tree Pruning," *IEEE Trans. Signal Processing*, vol. 56, pp. 4867-4878, 2008.

[14] R. Mesleh, H. Haas, C. Ahn, and S. Yun, "Spatial modulation – a new low complexity spectral efficiency enhancing technique," in *Proc. First International Conf. Commun. Netw.*, Beijing, China, pp. 1–5, Oct. 2006.

[15] A.Younis, N. Serafimovski , R.Mesleh, and H. Haas, "Generalised spatial modulation," *Signals, Systems and Computers (ASILOMAR), 2010 Conference Record of the Forty Fourth Asilomar Conference on*, pp.1498,1502, Nov. 2010

[16] J. Fu, C. Hou, W. Xiang, L. Yan, Y. Hou, "Generalised spatial modulation with multiple active transmit antennas," *GLOBECOM Workshops (GC Wkshps), 2010 IEEE* , pp.839,844, Dec. 2010.

[17] R. Böhnke, D. Wübben, V. Kuhn, and K. D. Kammeyer, "Reduced complexity MMSE detection for BLAST architectures," in *IEEE Global Telecommunications Conference, 2003. GLOBECOM '03,* vol. 4, pp. 2258-2262, 2003.

[18] J. F. Grcar, "Mathematicians of Gaussian elimination," *Notices of the American Mathematical Society*, vol. 58, pp. 782792, 2011.

[19] F. V. L. H.Golub, *Matrix computations*, vol. 4th. Baltimore: John Hopkins University Press, 2013.

[20] J. Benesty, H. Yiteng, and C. Jingdong, "A fast recursive algorithm for optimum sequential signal detection in a BLAST system," *IEEE Trans. Signal Processing*, vol. 51, pp. 1722-1730, 2003.

[21] A. M. Elshokry, "Complexity and Performance Evaluation of Detection Schemes for Spatial Multiplexing MIMO Systems," Faculty of Engineering, Islamic University Gaza, Gaza, Palestine, 2010.

[22] A. Younis, S. Sinanovic, M. Di Renzo, R. Mesleh, and H. Haas, "Generalised Sphere Decoding for Spatial Modulation," Communications, *IEEE Transactions on*, vol. 61, pp. 2805-2815, 2013.