Chapter 6

Improved Lattice Reduction Aided Large-MIMO Detection

In this chapter, an improved version of lattice reduction aided detector named as ILS detector is presented. The ILS detector is designed to achieve better performance in large MIMO and spatially correlated channels, especially in higher order QAM systems. The main motivation behind the work is that the performance-complexity tradeoff of lattice reduction aided detection is superior to most of the other detection approaches for higher order QAM constellations. Hence, the LR aided detection is considered and its BER performance is improved with a minimum additional computational overhead.

The main difference between the conventional lattice reduction aided detection and the work in this chapter are outlined as follows.

- A modified QRZ-LLL algorithm that offers relatively low complexity has been considered.

- A hybrid detection approach combining QRZ-LLL and depth first search is presented.
A multiple output selection strategy is employed. In this strategy, multiple searches are run to obtain candidate solutions and the best among them is selected. This is expected to improve the detection performance in low SNR regime and higher order constellations.

The BER performance and complexity are analyzed for $8 \times 8$, $16 \times 16$ and $32 \times 32$ MIMO systems in various correlation scenarios.

Lattice reduction (LR) has a good potential to achieve high performance MIMO detection and equalization at reasonably low complexity, which is suggested in works by Fischer et al. (2011) and Fischer (2012). Its practical importance is supported by recent VLSI implementations in Gestner (2011). Studies in Windpassinger et al. (2006) demonstrate the trade-off between complexity and power efficiency of lattice reduction based MIMO detectors. A survey of lattice reductions algorithms with its applications in wireless systems are extensively discussed in Wubben et al. (2011). Recent work by Zhou and Ma (2013a) and Zhou and Ma (2013b) provide low complex and efficient LR algorithms.

A brief overview of the works carried out on lattice reduction for correlated channels is presented here.

In Najafi et al. (2011), the effect of lattice reduction for the slowly varying fading channels, which exhibits temporal correlation, has been studied. Works have revealed that, for a MIMO-OFDM system in a channel with a large coherence bandwidth, the LR unimodular transformation matrices remain the same for many
adjacent subcarriers.

- In [Liu et al. (2012)](#), the relationship between channel coherence bandwidth and lattice reduction aided detection (LRAD) algorithms for MIMO-OFDM in frequency correlated fading channels has been analyzed.

- In [Wubben et al. (2004)](#), work has been reported on lattice reduction for spatially correlated channels using simplified Kronecker model. However, it fails to account certain critical issues like antenna configuration, the angular spread, number of rays and antenna spacing and different correlation at both TX and RX. The work in this chapter accommodates for the spatial correlation including the above factors.

The chapter is organized as follows. The improved LR aided detection via the hybrid approach is presented in section 6.1. The performance and complexity comparison of the improved LR method with the benchmark LR method is presented in section 6.2. The summary of work is provided in section 6.3.

### 6.1 Improved LRAD - Multiple output selection & Hybrid approach

This section deals with the hybrid approach for MIMO detection. The hybrid approach combines QRZ-LLL reduction and search, hence termed as improved lattice reduction and search (ILS). Lattice reduction is concerned with finding a shorter and improved basis representation of a given lattice, where both are related via unimodular trans-
formation. The procedure for lattice reduction aided detection include three major steps

- Improved basis is obtained via LR
- Detection is solved with reduced basis
- Solution is transformed to original domain via unimodular transformation.

Lattice reduction based MMSE-SIC \[ \text{Wubben et al. (2011)} \] technique performs the SIC detection with MMSE filter as sub-detector on the lattice reduced version of the extended channel matrix. Lattice reduction transforms the given basis \( H \) into new basis \( \tilde{H} \), where both are related via a unimodular matrix \( T \) as \( \tilde{H} = HT \). With proper shifting and scaling of the transmitted symbols, we can perform the LR based detection

\[
y = Hx + n = HTT^{-1}x + n = \tilde{H}s + n
\]  

(6.1)

Sorting of the channel matrix will improve the SIC detection and reduces degradation due to error propagation. For MMSE based approach, the channel matrix is extended as,

\[
H = \begin{bmatrix}
H \\
\sigma^2_m I_m
\end{bmatrix}
\]

and

\[
X = \begin{bmatrix}
x \\
0_{m,1}
\end{bmatrix}
\]
and the lattice reduction is applied on this extended channel matrix. For Successive interference cancelation, the QR decomposition is performed on this lattice-reduced matrix followed by employing the MMSE detector as the sub-detector.

\[ Z_{LR-MMSE-SIC} = \tilde{Q}^T X = \tilde{R}s + \hat{n} \] (6.2)

Finally, the detected symbols are transformed back to the actual solution domain via the unimodular matrix \( T \). Works in [Choi and Nguyen (2009)] show that LR-MMSE-SIC performance can be improved by combining with the list approach. However, the list approach is computationally arduous which prohibits its use in large MIMO systems. Recently low complex and efficient lattice algorithms were proposed by [Zhou and Ma (2013a)] for use in large MIMO systems, and the results reported confirms the superior performance over other large-MIMO detectors, especially in terms of performance-complexity trade-off.

### 6.1.1 Hybrid QRZ-LLL and Search strategy with multiple output selection

A hybrid approach for use in MIMO detection combining QRZ-LLL reduction and depth first search is presented. In addition, to improve the detection performance, multiple output selection strategy is employed. The multiple output selection has been earlier used [Li and Murch (2010)] to improve the performance of likelihood ascent detectors. The key steps in the algorithm are given below.

- The QRZ-LLL reduction listed in Fig. 6.1 is performed on the channel matrix
and the corresponding lattice transformation is applied on the received vector.

- The search algorithm in Fig. 6.2 is executed to obtain $M$ candidate solutions.

- The candidate solution that minimizes the ML cost function is chosen as the final solution.

### 6.1.2 QRZ-LLL reduction

The QRZ-LLL algorithms were first proposed by Chang and Golub (2009) as a computationally efficient method for ellipsoid constrained integer least squares problems. Recently some reductions in solving the integer least squares problem were investigated by Chang and Han (2008), Chang and Golub (2009) and Borno (2011). The studies analyzes efficient algorithms and their applicability in solving general integer least squares problem was illustrated. The studies by Borno (2011) shows that the QRZ-LLL reduction results in a matrix with better condition number and reduced orthogonality defect compared to the standard LLL algorithm. In addition, there is a saving of average running time which is reduced by a factor of 10 in the case of QRZ-LLL algorithm. In this section, we first review the procedure for QRZ-LLL lattice reduction. The LLL algorithm in Chang and Golub (2009) is used and the major steps are summarized below.

1. Start with QR decomposition and obtain the orthonormal matrix $Q$ and the upper triangular matrix $R$ for the original channel matrix $H$.

2. Obtain the permutation matrix $Z$ for lattice reduction.
3. Perform partial LLL reduction on $R$.

4. Perform a size reduction on $R$.

5. The above procedures are repeated for all the columns.

6. Transform $R$ back to an upper triangular matrix by a Givens rotation. The Givens rotation is preferred over other counterparts for its parallelization nature. This can be exploited in future for reducing the complexity further.

The received vector $y$ also undergoes a transformation with $Q^H$ and the subsequent given rotation as applied on $R$ in the lattice reduction. The process of QRZ-LLL consists of two major sub-processes. They are QR decomposition with column pivoting and partial LLL reduction presented. The algorithm for the QRZ-LLL reduction is presented in Fig. 6.1.

### 6.1.3 Multiple Search Strategy

The search algorithm is presented in this section. The search algorithm is based on Schnorr-Euchner strategy and it is applied on transformed $y$ and $R$ which are obtained as a result of applying the QRZ-LLL reduction. The search is typically a depth first search and it is continued till a full integer point inside the search ellipsoid is obtained. The search is performed sequentially layer by layer. The shrinking condition allows eliminating the points inside the search ellipsoid. As the search radius is set as $\beta = \infty$, the first point obtained in the search is the Babai integer point. The main reason for this approach is to improve the performance of LR based detector without increasing
Figure 6.1: Algorithm for QRZ-LLL reduction.

\begin{align*}
\text{Input} & \quad : H \; (\text{channel matrix}), \; y \; (\text{received vector}) \\
\text{Output} & \quad : R \; (\text{upper triangular matrix}), \; Z \; (\text{unimodular matrix}), \; \bar{y} \; (\text{transformed vector}) \\
\end{align*}

\textbf{Compute} \; H = QR \\
\bar{y} = Q^T \; y \\
Z = I_{n \times n} \\
k = 2 \\
\textbf{while} \; k \leq n \\
\textbf{for} \; i = k - 1; -1; 1 \\
\quad Z_{ji} = I - \mu e_i e_j^T, \; \mu \; \text{is an integer} \\
\quad R = RZ_{ji} \; (\text{Apply integer Gaussian transformation}) \\
\quad Z = ZZ_{ji} \\
\textbf{endfor} \\
\textbf{if} \; r_{k-1,k-1} > \sqrt{r_{k-1,k}^2 + r_{k,k}^2} \\
\quad \text{Interchange columns } k \; \text{and} \; k-1 \; \text{of} \; R \; \text{and} \; Z \\
\quad \text{Transform} \; R \; \text{to an upper triangular matrix by a Givens rotation} \\
\quad \text{Apply Givens rotation to} \; \bar{y} \\
\quad \text{if} \; k > 2 \\
\quad \quad k = k - 1 \\
\quad \text{else} \\
\quad \quad k = k + 1 \\
\textbf{end} \\
\textbf{endwhile}
the complexity significantly. A simple search is adopted here so that the computational
overhead for the search is not increased except for running multiple searches. The
anticipated performance improvement is attributed to the multiple output selection.
Hence, a simple search is sufficient for this combined approach. The Fig. 6.2 presents
the algorithm for the search process.

The search algorithm outputs $M$ candidate solutions and these solutions are stored
in a list. Finally there are $M$ candidate solutions and the best solution with lowest
maximum likelihood cost is chosen as the final solution. The value of $M$ is fixed
empirically and it will be the trade-off parameter between the computational complexity
and BER performance of this detector.

6.2 Numerical Results and Discussion

In this section, the ILS detector is applied to large-MIMO detection and its performance
is analyzed. Firstly, the QRZ-LLL reduction is applied on the MIMO channels and the
impact on correlated channels are studied. Subsequently, the hybrid ILS approach is
applied to MIMO detection and is analyzed in terms of the BER performance and
computational complexity. The MILES package developed by Chang and Zhou (2007)
is used for our implementation and numerical simulations. The performance of the
hybrid ILS approach is compared with the benchmark method which is the LR aided
MMSE-SIC detector in Zhou and Ma (2013a).
Input: $R$ (upper triangular matrix), $\bar{y}$ (transformed vector)

Output: $z$ (solution vector)

Initialization: $k = n$, $\beta = \infty$

Step 1: $c_k = \left( \frac{y_k - \sum_{j=k+1}^{n} r_{kj} z_j}{r_{kk}} \right)$, $k = n-1: -1: 1$

$z_k = \left\lfloor c_k \right\rfloor$

$\Delta_k = \text{sgn}(c_k - z_k)$

Step 2: if $r_{kk}^2 (z_k - c_k)^2 > \beta^2 - \sum_{i=k+1}^{n} r_{ii}^2 (z_i - c_i)^2$

  goto step 3

elseif $k > 1$

  $k = k - 1$

  goto step 1

else

  goto step 4

end

Step 3: if $k = n$

  stop

else

  $k = k + 1$

  goto step 5

end

Step 4: $\bar{z} = \bar{z}$

$\beta^2 = \sum_{i=1}^{n} r_{ii}^2 (\bar{z}_i - c_i)^2$

$k = k + 1$

goto step 5

Step 5: $z_k = z_k + \Delta_k$

$\Delta_k = -\Delta_k - \text{sgn}(\Delta_k)$

goto step 2

Figure 6.2: Search algorithm.
6.2.1 Impact of QRZ-LLL Reduction on spatially correlated channels

In this section, the impact of QRZ-LLL lattice reduction on the spatially correlated MIMO channels is analyzed. The QRZ-LLL reduction is applied on uncorrelated channels and spatially correlated channels with correlation at either and both the transmitter - receiver ends. The impact of spatial correlation and the effect of applying QRZ-LLL reduction is illustrated on an $8 \times 8$ MIMO channel. The study pertains to the condition number which refers to the usual 2-norm condition number defined as the ratio of the largest singular value to the smallest. A degradation factor of the condition number is computed as the difference in probability measure between the uncorrelated and correlated channels normalized with respect to the uncorrelated channel.

![Figure 6.3: CDF of condition number of an $8 \times 8$ MIMO channel. (org. original uncorrelated, corr. correlated at both ends, Tx/Rx. corr. correlated at one end, red. lattice reduced)](image)

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Fig. 6.3 depicts the c.d.f (cumulative distribution function) curves for an $8 \times 8$ MIMO channel. It can be seen that, as the order of MIMO system increases, generally the condition number of the matrix becomes poorer, which is the reason for degraded performance of certain sub-optimal schemes in large MIMO channels with tens of antennas. The impact of employing lattice reduction is more encouraging, in the sense that, all the three c.d.f curves - reduced version of the original channel matrix, correlated at one end and correlation at both the ends, follow a similar distribution. This clearly shows that as the order of MIMO system increases, i.e. increase in the number of antenna terminals, the effect of spatial correlation is reduced largely by employing lattice reduction on the channel matrix. The degradation factor of condition number nearly approaches zero, indicating no significant loss in the condition number of the channel matrix. As the number of antennas increases to 16 or above, the c.d.f of the original and reduced channels overlaps showing no difference. This motivates the use of QRZ-LLL reduction for MIMO detection spatially correlated channels.

6.2.2 Performance analysis in large MIMO systems

In this section, the BER performance of ILS detector in various MIMO configurations including for $8 \times 8$, $16 \times 16$ and $32 \times 32$ employing 16-QAM constellations are presented. The value of $M$ is fixed in the range of 3 to 5. The benchmark for comparison is the LR-MMSE-SIC detector in Zhou and Ma (2013a).

In Fig. 6.4 the performance comparison of the ILS detector and the LR aided MMSE-SIC detector is compared in $8 \times 8$ MIMO. It is observed that the ILS detector
Figure 6.4: BER performance comparison of ILS & LR-MMSE-SIC detectors in $8 \times 8$ MIMO with 16-QAM in uncorrelated channels.

Figure 6.5: BER performance comparison of ILS & LR-MMSE-SIC detectors in $16 \times 16$ MIMO with 16-QAM in uncorrelated channels.
Figure 6.6: BBER performance comparison of ILS & LR-MMSE-SIC detectors in 32×32 MIMO with 16-QAM in uncorrelated channels.

offers a gain around 2 dB over LR-MMSE-SIC detector. From Fig. 6.5, it is observed that the gain offered by ILS detector in 16×16 MIMO increases to nearly 3 dB. This implies that as the MIMO size increases, the gain offered by the ILS detector also increases. Fig. 6.6 depicts the performance in 32×32 MIMO. The SNR gain offered by ILS over LR-MMSE-SIC detector is consistent and it is around 3 dB. The results show that with increased MIMO dimension, the ILS detector exhibits consistency in outperforming the LR-MMSE-SIC detector. This result demonstrates that the proposed ILS is probably a good choice for higher order QAM constellations in large-MIMO systems.
6.2.3 Performance analysis in spatially correlated channels

The discussion in the earlier section substantiated the advantage of the ILS detector in uncorrelated large-MIMO systems. Now, the focus of study is towards the correlated channels. In this section, the performance in spatially correlated channels is presented for the ILS detector and LR-MMSE-SIC detector in Zhou and Ma (2013a). All cases of correlation including low correlation \((p = 0)\), medium correlation \((p = 0.3)\) and high correlation \((p = 0.7)\) are considered. The results are presented for 8\(\times\)8, 16\(\times\)16 and 32\(\times\)32 MIMO systems.

![Figure 6.7: BER performance comparison of ILS & LR-MMSE-SIC detectors in 8 \(\times\) 8 MIMO with 16-QAM in low correlated channels.](image)

Fig. 6.7 to Fig. 6.9 shows the performance comparison of the ILS detector with LR-MMSE-SIC method in spatially correlated 8 \(\times\) 8 MIMO, with 16-QAM mapping. The performance characteristics in low to medium SNR is as follows. From Fig. 6.7,
Figure 6.8: BER performance comparison of ILS & LR-MMSE-SIC detectors in $8 \times 8$ MIMO with 16-QAM in medium correlated channels.

Figure 6.9: BER performance comparison of ILS & LR-MMSE-SIC detectors in $8 \times 8$ MIMO with 16-QAM in high correlated channels.
it is observed that the ILS detector offers a gain of 1.5 dB over LR-MMSE-SIC for low correlated channels. The gain slightly reduces for medium correlation and is around 1 dB as observed from Fig. 6.8. In high correlated channels as depicted by Fig. 6.9, the gain is around 0.75 dB. For high SNRs, the ILS offers a gain of 2 dB over the LR-MMSE-SIC in low and medium correlated scenarios in high SNR regime and the gain reduces to close to 1 dB in high correlated channels.

From Figs. 6.10 to 6.12 the performance comparison in $16 \times 16$ MIMO for low, medium and high correlation scenarios are depicted. The performance curves of the ILS detector take a deviation at 12 dB for low correlated channel, and at 15 dB for medium and high correlations. The SNR gain is around 3 dB for all the correlated conditions after this deviation. The gain has increased significantly for $16 \times 16$ MIMO compared
Figure 6.11: BER performance comparison of ILS & LR-MMSE-SIC detectors in $16 \times 16$ MIMO with 16-QAM in medium correlated channels.

Figure 6.12: BER performance comparison of ILS & LR-MMSE-SIC detectors in $16 \times 16$ MIMO with 16-QAM in high correlated channels.
to $8 \times 8$ MIMO. This demonstrates the large system behavior of the ILS detector in spatially correlated channels. Further we note that, with increased MIMO size, the ILS detector can offer a better performance compared to LR-MMSE-SIC detector even in severe correlation conditions. For instance, the performance of ILS for $p = 0.5$ is better than the performance of LR-MMSE-SIC for $p = 0.3$ in high SNR regime. However, the ILS and LR-MMSE-SIC detectors show similar performance in low SNR conditions.

![Figure 6.13: BER performance comparison of ILS & LR-MMSE-SIC detectors in 32×32 MIMO with 16-QAM in low correlated channels.](image)

The performance in $32 \times 32$ MIMO system is presented in Fig. 6.13, Fig. 6.14 and Fig. 6.15 respectively. The trend is encouraging and it supplements the claim of large system behavior of the ILS detector. The performance gain over LR detectors is identical to that of $16 \times 16$ MIMO except that the deviation is noted around 12 dB for low and medium correlated scenarios, while it occurs around 15 dB for high correlation.
Figure 6.14: BER performance comparison of ILS & LR-MMSE-SIC detectors in 32×32 MIMO with 16-QAM in medium correlated channels.

Figure 6.15: BER performance comparison of ILS & LR-MMSE-SIC detectors in 32×32 MIMO with 16-QAM in high correlated channels.
The gain of ILS detector over LR-MMSE-SIC detector is slightly over 3 dB in the region after this drift. The LR-MMSE-SIC performs slightly better than the ILS detector in low SNR regime. However, the gain is not significant.

The results demonstrate the superior performance of the ILS detector over LR-MMSE-SIC detectors in spatially correlated channels and large-MIMO systems. The ILS detector offers a minimum gain of around 3 dB for $16 \times 16$ and $32 \times 32$ MIMO systems. It is encouraging to note that the performance gain improves with increase in the MIMO size, thus substantiating the large system behavior. The BER performance results suggest that the ILS detector exhibits superior performance over the LR-MMSE-SIC detector in both uncorrelated and spatially correlated channels.

### 6.2.4 Complexity Comparison

The superior performance of ILS detector is at the cost of some extra computational burden. This is due to the reason that the depth first search is computationally complex than simple MMSE filter. The multiple searches will incur some additional computational time. In this section, the computational cost of the ILS detector is analyzed. The computational complexity of ILS detector is estimated in terms of average execution time required to detect a symbol.

The comparison between the LR-MMSE-SIC detector in Zhou and Ma (2013a) and the ILS method for uncorrelated as well as correlated channels in all MIMO configurations are presented in Table 6.1. The major inferences are as follows.

1. In uncorrelated channels, ILS detector offers a gain of 2 dB for $8 \times 8$ MIMO and 3
Table 6.1: Performance and Average Execution Time comparison of the ILS & LR-MMSE-SIC detectors in $8 \times 8$, $16 \times 16$ and $32 \times 32$ large-MIMO systems.

For BER of $10^{-2}$, 16-QAM system, SNR in dB & Average Running Time(ART) in sec

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>SNR</th>
<th>ART</th>
<th>SNR</th>
<th>ART</th>
<th>SNR</th>
<th>ART</th>
<th>SNR</th>
<th>ART</th>
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<tbody>
<tr>
<td></td>
<td>p=0</td>
<td></td>
<td>p=0.3</td>
<td></td>
<td>p=0.5</td>
<td></td>
<td>p=0.7</td>
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<tr>
<td>8 $\times$ 8 MIMO</td>
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<td></td>
</tr>
<tr>
<td>LR-MMSE-SIC</td>
<td>15.5</td>
<td>8.8E-6</td>
<td>16</td>
<td>8.8E-6</td>
<td>18</td>
<td>8.8E-6</td>
<td>21</td>
<td>8.8E-6</td>
</tr>
<tr>
<td>ILS</td>
<td>13.75</td>
<td>1.3E-5</td>
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<td>1.3E-5</td>
<td>16.75</td>
<td>1.3E-5</td>
<td>20</td>
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</tr>
<tr>
<td>16 $\times$ 16 MIMO</td>
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<tr>
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<td>1.3E-5</td>
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<td>14.75</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>LR-MMSE-SIC</td>
<td>19</td>
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<td>19.75</td>
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<td>3.1E-5</td>
<td>28</td>
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<td>ILS</td>
<td>16</td>
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<td>16.75</td>
<td>3.9E-5</td>
<td>18</td>
<td>5.9E-5</td>
<td>23</td>
<td>8.2E-5</td>
</tr>
</tbody>
</table>

dB for $16 \times 16$ and $32 \times 32$ MIMO respectively. The gain increases as the MIMO size increases.

2. In $8 \times 8$ MIMO, the SNR gap reduces as the correlation increases. It is around 2 dB in uncorrelated and decreases to 1 dB in high correlation.

3. In $16 \times 16$ and $32 \times 32$ MIMO systems, the SNR gap increases with increase in correlation. This means that the actual advantage of multiple output selection is realized in large MIMO sizes.

4. Further, the degradation in performance from uncorrelated to correlated channels in ILS detector is slower compared to LR-MMSE-SIC.

5. The execution time of the ILS detector is slightly on the higher side, but it is justified with the performance improvement offered, which is minimum 2 to 3 dB in uncorrelated channels and 4 to 5 dB in correlated channels. This increased
complexity is due to the $M$ searches, which is essential to improve the BER performance.

6.3 Summary

In this chapter, the impact of QRZ-LLL reduction on the spatially correlated channels with different correlation scenarios has been studied. The degradation on the condition number of the channel when subjected to spatial correlation was analyzed and it is shown that the QRZ-LLL reduction improves the conditioning of the matrix even in the correlated scenarios. This stands a motivation for the probable use of QRZ-LLL reduction in large MIMO channels (order of tens) in the presence of spatial correlation.

The ILS method - hybrid QRZ-LLL reduction and a depth first search strategy with multiple output selection was presented and applied to the detection in large-MIMO systems. The results demonstrate that the proposed ILS method performs superior to conventional lattice reduction aided detection in all MIMO configurations and correlation conditions.

In uncorrelated channels, ILS detector offers a 1 dB gain in $8 \times 8$ MIMO, whereas the gain increase to 3 dB in $16 \times 16$ MIMO and $32 \times 32$ MIMO systems. In $8 \times 8$ MIMO, the ILS detector offers an average gain of 1.5 dB compared to the LR-MMSE-SIC detector in all correlated conditions. In $16 \times 16$ and $32 \times 32$ MIMO systems, the average gain is around 4 dB for all correlation conditions. This implies that the ILS detector exhibits large system behavior, i.e. improved performance as MIMO size increases. In general, the ILS detector outperforms LR-MMSE-SIC detector and the gain is prominent with
increase in MIMO size and correlation depth.

We conclude that the lattice reduction aided detection turns out to be a viable solution to counteract the effect of spatial correlation in large-MIMO systems employing higher order constellations. However, further investigations are required to reduce the complexity, in terms of execution time by exploiting probable parallelization.