Complexity Reduction in Massive MIMO Using Hybrid Lattice Reduction Technique

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Abstract: Wireless communication has become an integral element of the lives of millions of people. Propagation losses, which are larger at very high frequencies, are one of the most typical issues that come to mind. Massive multiple-input multiple-output (MIMO) is one of the most promising technologies for the future generation of wireless communication networks because it has the ability to achieve increasing spectral efficiency (SE) and energy efficiency (EE) while also reducing complexity. We focused on the Lattice reduction method in our proposed work, which was combined with MIMO Equalizers to create a new hybrid receiver detection method. The LLL lattice method is coupled with MMSE and ZF linear receivers to increase spectral efficiency while reducing BER and implementation complexity. We are testing the suggested LLL-ZF and LLL-MMSE algorithms with single user configurations to demonstrate system compatibility and comparing it to the ML detector. For this suggested algorithm and the accompanying findings, we also consider a scattering based channel model. Improvements are studied, and it is discovered that there is a nearly 56% gain in ELLL-ZF and a 50% gain in ELLL-MMSE in complexity when compared to the ML detector.

IndexTerms— MIMO, Massive MIMO, Lattice Reduction, Receiver Detection, Low complexity, MMSE

I. INTRODUCTION

The over the last two decades, wireless communications advances have improved the economic education and social development of many countries. Wireless communication has now become a critical element of millions of people's lives. Data rates are predicted to increase much further, a variety of other types of communication, and the fifth generation (5G) of mobile communications is expected to deliver this satisfaction. Because the 5G criteria for data rates and capacity are so demanding, only a few new technologies and spectrums have been introduced to address these issues. The problem of propagation losses, which are higher at high frequency, is one of the most typical challenges that comes to mind.

To keep up with the growing wireless traffic, every network must increase its data speed. By boosting spectral efficiency (bits/s/Hz/cell), Massive MIMO technology can provide a ten-fold increase in area throughput while employing the same bandwidth and density of base stations as present networks. These enormous increases are made possible by equipping the BS with hundreds of antenna arrays that enable spatial multiplexing and beamforming to serve several customers at the same time. This technique can be applied in a variety of antenna configurations, and we'll look at Uniform Linear Array (ULA) using Massive MIMO technology theory and principles. The design of radio frequency (RF) antenna systems is particularly complex in the creation of wireless systems. Designing high-performance, low-complexity MIMO detectors, on the other hand, is extremely challenging. Although the maximum likelihood detector is recognized to have the best error performance, its complexity grows exponentially as the number of transmit antennas grows[1]. The employment of a sequential interference cancellation (SIC) detector helps minimize complexity, but due to diversity loss, these detectors perform poorly[2]. Recently, good performance and reasonable complexity have benefited lattice reduction helped SIC greatly[3]. The Lenstra Lenstra Lovasz (LLL)[4] is a popular choice because of its polynomial complexity. One of the key disadvantages of the LLL algorithm is its variable complexity, which makes it unsuitable for hardware implementation due to its non-deterministic iteration.

This research primarily focuses on the Bit Error Ratio (BER) of Massive Multiple-Input Multiple-Output (mMIMO) Systems with LLL reduction technique hybrid with linear detection of Zero Forcing (ZF) and comparing it to the LLL hybrid with Minimum Mean Square Error (MMSE) detection system. We will look at the complexity of the proposed hybrid method in terms real number operation.

The remainder of the paper is laid out as follows: The Massive MIMO system's system model and channel models are described in Section II. The derivations of suggested hybrid LR methods LLL-ZF and LLL-MMSE are introduced in Section III. We offer experimental data for the Massive MIMO system in Section IV, followed by a discussion of how the two systems compare in terms of performance. Finally, Section V brings this paper to a conclusion.

II. SYSTEM ARCHITECTURE OF MASSIVE MIMO AND CHANNELS

1) Massive MIMO System model

Because wireless spectrum has grown increasingly congested and expensive, particularly below the 6 GHz frequency band, MIMO scaling enables a significantly greater degree of spatial freedom than any of today's systems. Large scale MIMO systems have up to eight antennas, whereas very large or gigantic MIMO systems have more than eight antennas. In a MU-massive MIMO system, an access point can connect with multiple subscribers at the same time using the same frequency resource. The majority of processing takes place at base stations, which are equipped with inexpensive and basic hardware.
The number of communication systems and antennas used by different applications varies. In this study, we look at MU-Massive MIMO technology in cellular systems, where a base station has tens to hundreds of antennas and uses spatial multiplexing to connect with multiple users at the same time [7]. Figure 1 depicts the MU-MIMO system model for a single cell in both downlink and uplink transmissions. However, MIMO with a large number of antennas should not be restricted to multi-user settings. It can also be utilized in single-user applications, such as base station backhaul lines.

![Figure 1. Massive MIMO System Model](image)

Returning to Figure 1, in the spatial domain, an M-antenna base station multiplexes K single-antenna users. For each time-frequency resource, the downlink signal model is

\[ y = \sqrt{p_{dl}} H z + n \]  

(1)

Where \( H \) is the propagation channel matrix, \( z \) is the vector of precoded transmit signals across the M antennas, \( y \) is the receive signal vector at the K users, and \( n \) is the white-noise vector with i.i.d. circularly-symmetric complex Gaussian elements. \( p_{dl} \) contains the total transmit power in the downlink as below,

\[ p_{dl} = \frac{\rho K}{M} \]  

(2)

where \( \rho \) is an SNR factor. We scale up the transmit power with the number of users \( K \), and choose to keep it constant or scale it down with the number of antennas \( M \).

Due to reciprocity, the uplink channel matrix is \( H^T \), and the signal model becomes

\[ z = \sqrt{p_{ul}} H^T y + n \]  

(3)

The total transmit power from all users is \( p_{ul} \), \( p_{ul} = \rho K \) or \( p_{ul} = \frac{\rho K}{M} \) depending on used power-scaling scheme. In massive MIMO, we usually assume \( M > K \), for achieving good spatial separation of user signals.

2) Channel model of Massive MIMO

For validation, we looked at the spatial MIMO channel as well as a simpler static-flat MIMO channel. The scattering model employs a parametrized number of scatterers and a single-bounce ray tracing approximation. Similar to the one-ring model [12], the 'Scattering' option models scatterers distributed randomly within a sphere around the receiver. Path-loss modeling and non-LOS propagation conditions are possible with the channel models. Non-LOS propagation is assumed, as well as isotropic antenna element designs with linear or rectangular geometry.

The signal is transmitted over a narrowband block-fading propagation channel such that the \( N_r \times 1 \) received analog signal vector \( y \) at the receiver’s antennas is,

\[ y = \sqrt{p_r} H F_{RF} F_{BB} s + n \]  

(4)

where \( H \) is the \( N_r \times N_t \) channel matrix, \( p_r \) is the received average power and \( n \) is an \( N_r \times 1 \) noise vector with zero mean. In fig 5, we shown the overall block diagram of the system.

III. PROPOSED HYBRID LR METHODOLOGY

Lattice reduction (LR) [17] is a powerful and efficient algorithm to improve system performance with reduced complexity [18]. The basic approach of the LR-aided receiver system is to convert the lattice basis formed by the channel matrix into a near orthogonal lattice basis. The existence of this short and orthogonal basis leads to a tremendous improvement in the MIMO system performance [19, 20]. Extensive research work is ongoing, and different variants of LR algorithms have been proposed. In this work we have proposed the MIMO equalizers combined with Lenstra–Lenstra–Lovász algorithm (LLL) algorithm.

Let considers \( N_t \times N_r \) MIMO system having \( N_t \) transmitting antennas and \( N_r \) receiving antennas. The MIMO system equation can be written as

\[ Y = H x + n \]  

(5)
where the transmit signal, $x$, is involved with time varying flat fading wireless channels, $H$. Here, $n$ is the $N_r \times 1$ additive white Gaussian noise (AWGN) vector and $E[xx^H] = (\rho/N_t) I$. In this case, the CSI is assumed to be perfectly known to both the transmitter and the receiver.

1). **LLL-Zero Forcing equalization**

The complete suppression of the interference has been made possible by ZF receiver [21]. In addition, it is done by taking the pseudo inverse of the channel matrix.

$$H^{zf} = (\tilde{H}^T \tilde{H})^{-1} \tilde{H}^T$$  \hspace{1cm} (6)

Where $\tilde{H}$ is LR based decomposed channel matrix. LR algorithm produces the reduced channel matrix. As in MIMO QR processing is very commonly used, the LLL algorithm is modified for the Q and R matrices. The LR algorithm is applied in the QR decomposed $H$ to find the $\tilde{Q}$ and $\tilde{R}$. Furthermore, those can be used to obtain the reduced channel matrix, which is defined as

$$\tilde{H} = \tilde{Q} \tilde{R}$$  \hspace{1cm} (7)

Where $\tilde{Q} = QT$ and $\tilde{R} = RT$. $T$ is a unimodular matrix. Therefore, the massive MIMO system of LLL-ZF equation can be rewritten as from equ (5),

$$Y = H^{zf} z + n$$  \hspace{1cm} (8)

Where $z = T^{-1} x$. The output SNR for of the nth branch for the LLL-ZF receiver is given by,

$$\rho_{zf,n} = \frac{\rho}{[H^{zf} H^{zf} I]_{nn}} , 1 \leq n \leq N_t$$  \hspace{1cm} (9)

The problem in the ZF receiver appears when there are ill-conditioned $H$ matrices and this leads the increase in noise variance after the matrices inversion. Without noise, ZF acts as an optimal receiver similar to ML. However, it produces a noise amplification. By combining the linear receiver with the LLR algorithm, the LLL-ZF system performance can be further improved. Moreover, this approach can reduce the performance gap between the conventional linear receiver and the optimal ML receiver.

2). **LLL-MMSE Equalization**

To eliminate the effect of noise amplification due to the ZF receiver, a more robust equalizer, MMSE receiver, has been introduced [24]. MMSE based channel matrix can be defined as,

$$H^{mmse} = (\tilde{H}^T \tilde{H} + \frac{N_t}{\rho} I)^{-1} \tilde{H}^T$$  \hspace{1cm} (11)

Where $\tilde{H}$ is LR based decomposed channel matrix and can referred from equ (14).

Therefore, the massive MIMO system of LLL-MMSE equation can be rewritten as from equ (12),

$$Y = H^{mmse} z + n$$  \hspace{1cm} (12)

Where $z = T^{-1} x$. The output SNR for of the nth branch for the LLL-MMSE receiver is given by,

$$\rho_{mmse,n} = \frac{\rho}{[H^{mmse} H^{mmse} I]_{nn}} , 1 \leq n \leq N_t$$  \hspace{1cm} (13)

The MMSE receiver takes care of both noise and interference. Furthermore, the MMSE receiver provides an improved solution for the ill-conditioned $H$ matrices, hence provides improved performance in comparison to the ZF receiver. In terms of complexity, the LLL-MMSE receiver is much less complex than both ZF and MF detectors.

**IV. PERFORMANCE ANALYSIS**

In this section, we performed the analysis of proposed Hybrid LR design of LLL-ZF and LLL-MMSE with perfect CSI of massive MIMO. Also we illustrated the effectiveness of default massive MIMO channel with our proposed algorithm. To demonstrate the effectiveness of the proposed methods in the unconstrained case of massive MIMO system, we evaluate the BER and complexity for both LLL-ZF and LLL-MMSE configurations. We analyzed the performance of Single user Massive MIMO with the different parameters as mentioned in the below Table I. The considered simulation parameters are according IEEE 802.11ax which serves four spatial data stream in the available BW.
Table I. Common Simulation Parameter Configurations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation Type</td>
<td>16 QAM</td>
</tr>
<tr>
<td>Number of Data symbols</td>
<td>32</td>
</tr>
<tr>
<td>FFT size</td>
<td>256</td>
</tr>
<tr>
<td>CP length</td>
<td>64</td>
</tr>
<tr>
<td>Ntx</td>
<td>32</td>
</tr>
<tr>
<td>Nrх</td>
<td>32</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>28 GHz</td>
</tr>
<tr>
<td>BS Coverage Range</td>
<td>1000 m</td>
</tr>
<tr>
<td>Channel Sampling Rate</td>
<td>100 Msps</td>
</tr>
<tr>
<td>Noise Figure</td>
<td>5 dB</td>
</tr>
<tr>
<td>Code Rate</td>
<td>1/3</td>
</tr>
<tr>
<td>MIMO Equalization</td>
<td>Zero Forcing and MMSE</td>
</tr>
<tr>
<td>SNR Range</td>
<td>0-30 dB</td>
</tr>
<tr>
<td>Antenna Spacing distance</td>
<td>λ/2</td>
</tr>
<tr>
<td>Number of Users</td>
<td>1</td>
</tr>
<tr>
<td>Phased Array</td>
<td>ULA</td>
</tr>
<tr>
<td>Hybrid Beamforming</td>
<td>Orthogonal Matching pursuit (OMP)</td>
</tr>
<tr>
<td>Channel Model</td>
<td>One Ring based Scattering Channel Model</td>
</tr>
</tbody>
</table>

Figure 2. BER Vs SNR in Scattering channel model for K=1, N_s=4, n_{iteration}=22, 16QAM

BER is a critical parameter to evaluate the performance of a receiver. In fig 2, shows that the proposed detectors are compared with linear detection technique ZF and optimal detection technique ML. At lower SNR value difference between BER value are less while increasing SNR values, proposed detectors follows ML detection technique. In fig 2, at 29dB the BER achieved by ZF, proposed ELLL-ZF, and ELLL-MMSE is 0.2436, 0.008398 and 0.004199 respectively, which show that increasing SNR the BER value decreases. A large gap between ZF and proposed LLL-ZF and MMSE is obtained which is approximately a gain of 13dB.

Fig 3 shows the 3D beam pattern obtained when spatial multiplexing is used to sent multiple data stream to a user. Fig a is the transmitting beam pattern while fig b is receiving beam pattern. As discussed in section II we are using full complexity hybrid architecture at both transmitter and receiver. So a receiving beam pattern using phased array antenna is obtained. The stronger lobes are representing the number of data stream sent to a user. Further in fig 4 the proposed ELLL-ZF and ELLL-MMSE is compared with various Lattice reduction algorithms. Brun’s algorithm, LLL, CLLL, FCLLL and ELLL is providing a straight line with increasing SNR when four data streams are sent to single user. This shows that there is very high BER when these four LR algorithms are used. Further possible Swap LLL algorithm, Greedy LLL Algorithm, and proposed ELLL-ZF and ELLL-MMSE is shows variation in BER when SNR is increasing and ELLL-MMSE is obtaining the most optimal result in all these algorithms considered.

Here we have shown the complexity aspect of our proposed algorithm and we compare it with the most optimal ML method. The fig 5 above shows the complexity calculation of proposed algorithms in terms of real addition and multiplication.
Here we have shown the complexity aspect of our proposed algorithm and we compare it with the most optimal ML method. The fig 5 above shows the complexity calculation of proposed algorithms in terms of real addition and multiplication.

In this section the complexity of proposed detectors is computed in terms of number of real additions and multiplication required for the fixed number of iteration i.e $n_{\text{iteration}} = 22$ and the results are straightforward compared with ML technique. The LLL algorithm pre-processing stage involves performing QR decomposition, which has a complexity of $8N_rN_t^2 - 2N_rN_t - M^2 + M$, where $N_t$ is the transmitting antenna, $N_r$ is the receiving antenna and M is the modulation order.
Proposed ELLL-ZF provides the lowest complexity with number of addition equal 7311 and number of multiplication equal 9744 in case of SU with number of data stream being served is four. To calculate the total complexity gain one real multiplication is assumed to be equal to four real additions. So the total complexity is converted into real addition and complexity is calculated with compared to optimal detector ML. In this way when single user is considered a gain of 56% in modified ELLL-ZF and 50% in modified ELLL-MMSE as compared to ML is obtained.

Figure 5. Complexity Measure of proposed algorithm

Table III: Complexity Calculation

<table>
<thead>
<tr>
<th>Detection Method</th>
<th>Complexity Calculation in term of addition and multiplication.</th>
<th>Addition</th>
<th>Multiplication</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELLL-ZF</td>
<td></td>
<td>7311</td>
<td>9744</td>
</tr>
<tr>
<td>ELLL-MMSE</td>
<td></td>
<td>11860</td>
<td>6116</td>
</tr>
<tr>
<td>ML</td>
<td></td>
<td>16580</td>
<td>7980</td>
</tr>
</tbody>
</table>

V. CONCLUSION

This paper discusses the effectiveness of the lattice reduction-aided receivers for massive MIMO systems. In this paper, we analyze the hybrid based lattice reduction algorithms of ZF and MMSE. The performance of the massive MIMO system is analyzed in terms of the improvement in BER. Through the mathematical calculation and simulated results, this study showed that the lattice reduction-aided receivers outperform the conventional linear receivers. Main focus of complexity reduction also achieved in our proposed of 56% and 50% reduced computations than optimal ML receivers in ELLL-ZF and ELLL-MMSE. As an extension of the presented work, we plan to focus on the study of performance for millimeter wave massive with this proposed hybrid LR method.

REFERENCES


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