Implementation and Complexity Analysis of List Sphere Detector for MIMO-OFDM systems

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Outline

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- List Sphere Detector (LSD)
- Example case: IR-LSD implementation
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Introduction

- Orthogonal frequency division multiplexing (OFDM), which simplifies the receiver design, has become a widely used technique for broadband wireless systems.
- Multiple-input multiple-output (MIMO) channels offer improved capacity and potential for improved reliability compared to single-input single-output (SISO) channels.
- MIMO technique in combination with OFDM (MIMO-OFDM) has been identified as a promising approach for high spectral efficiency wideband systems.
  - 3GPP LTE, WiMax.
A MIMO-OFDM system

- OFDM based multiple antenna system with $N_T$ transmit and $N_R$ receive antennas
- Received signal $y = Hx + \eta$
  
  where $H$ is the channel matrix,
  $x$ is the transmitted symbol vector,
  $\eta$ is a noise vector.

![A MIMO-OFDM system model](image-url)

Figure 1: A MIMO-OFDM system model
Detection in a MIMO-OFDM system

- Detection means that the detector calculates an estimate of the transmitted signal vector $\mathbf{x}$ as an output of the detector
  - Transmitted signal vector $\mathbf{x}$ includes $N_T$ different symbols
- The OFDM technique simplifies the receiver structure by decoupling frequency selective MIMO channel into a set of parallel flat fading channels
  - Different data is sent in different subcarriers
- However, the reception of the signal has to done separately for each subcarrier
  - E.g. in 3GPP LTE standard 512 subcarriers (300 used) with 5MHz bandwidth (BW) and the the interval of OFDM symbol is 71$\mu$s
  - Thus, detector must calculate an estimate of $300 \times N_T$ symbols in 71$\mu$s
Detection for MIMO-OFDM (cont)

- The use of maximum a posteriori (MAP) detector is the optimal solution for soft output detection
  - In practice coded systems are used, i.e., soft output detection is applied
  - The calculation of maximum likelihood (ML) and MAP solutions with conventional exhaustive search algorithms is not feasible with large constellation and high number of transmit antennas
- Suboptimal linear minimum mean square error (LMMSE) and zero forcing (ZF) criterion based detectors feasible with reduced performance
- Sphere detectors (SD) calculate ML solution with reduced complexity
  - List sphere detector (LSD) [1] is an enhancement of SD that can be used to approximate the MAP detector
- Sphere detectors still much more complex compared to LMMSE or ZF detectors
  - Linear detectors calculate a weight matrix $\mathbf{W}$ which can be possibly be used for multiple subcarriers and OFDM symbols
    - Depending on the channel coherence time and frequency
  - SD and LSD execute a tree search always separately for each subcarrier and OFDM symbol
List Sphere Detector

- List sphere detector [1] executes a tree search on a lattice formed by the channel matrix
  - Gives a list $\mathbf{L}$ of candidate symbol vectors as an output
  - The candidate list can be used to approximate the soft output information $L_D(b_k)$
  - The list size $|\mathbf{L}|$ affects the quality of the approximation and depending on the list size, the LSD provides a tradeoff between the performance and the computational complexity

- Tree search algorithms divided mainly into two categories:
  - Sequential search: depth first, metric first
    + Optimal solution
    - Variable throughput, dependent on the channel realization
  - Breadth first algorithms
    + Fixed throughput
    + Can be implemented using parallel architecture
    - More complex in terms of visited nodes
    - Not an optimal solution
List Sphere Detector (cont)

- The ML solution is the vector $\mathbf{x}$ which minimizes
  \[ \hat{\mathbf{x}}_{ML} = \arg \min_{\mathbf{x}} \| \mathbf{y} - \mathbf{Hx} \|_2^2 \]

- The channel matrix $\mathbf{H}$ is decomposed with QR decomposition (QRD) as
  \[ \| \mathbf{y} - \mathbf{QRx} \|_2^2 \leq C, \]
  \[ \| \tilde{\mathbf{y}} - \mathbf{Rx} \|_2^2 \leq C. \]

- Due to upper triangular form of $\mathbf{R}$ the values of $\mathbf{x}$ can be solved level by level.

- Thus, the SD and LSD search can be illustrated with a tree structure.

Figure 2: 2Tx antennas, 4 quadrature amplitude modulation (QAM) (real decomposition)
List Sphere Detector (cont)

- The LSD architecture consists of three main parts:
  - The preprocessing algorithm, e.g., QRD
  - The LSD algorithm, e.g., K-best algorithm
  - The LLR calculation, e.g., Max-log-MAP approximation

- Algorithm modifications for implementation:
  - Real and complex signal model compared [2]: Real model less complex in general
  - Search with limited maximum number of nodes studied [2]: Enables fixed maximum complexity for hardware implementation
  - The LLR clipping prevents the problems due to inaccurate soft output approximation [3]: Enables the use of lower list size -> Reduces required complexity

Figure 3: A high level architecture of LSD.
Example case: IR-LSD implementation

- The increasing radius (IR)-LSD implementation is introduced [4]
  - Sorted QRD
  - IR-LSD algorithm
  - Max-log-MAP approximation

- The implementation process includes different phases:
  - Algorithm modification for implementation
  - Architecture design
  - Word length study
    - Fixed-point or floating point representation
  - Register transfer level (RTL) description
    - VHDL, Verilog
  - Synthesis, and place and route
    - FPGA, DSP, ASIC
Example case: IR-LSD architecture

- The architecture includes five units
  - Two SEE and PED units
  - Final candidate memory
  - Partial candidate memory
  - Control logic unit

- Architecture operates in a sequential fashion
  - Two tree nodes calculated in one iteration
  - Variable number of iterations executed depending on the system configuration

Figure 4: The IR-LSD algorithm architecture.
Example case: IR-LSD architecture

- The LLR calculation unit applies Max-Log-MAP approximation to calculate the soft output information $L_D(b_k)$
  - Microarchitecture illustrated in Figure 5
  - Different levels of parallelism and pipelining can be applied
    - Scaling of ED values (parallel MUL)
    - The m- and k-loops logic can be implemented in parallel and with pipelining

![Figure 5: The LLR calculation unit microarchitecture.](image)
Example case: IR-LSD implementation

- A field programmable gate array (FPGA) implementation
  - 4x4 system with 16-QAM constellation
  - Fixed-point word lengths determined
  - Virtex-IV device utilization and latency numbers

### TABLE I
WORD LENGTHS FOR THE IR-LSD IN A 4 × 4 SYSTEM WITH 16-QAM.

<table>
<thead>
<tr>
<th>SQRD (W,I)</th>
<th>H (11,3)</th>
<th>R (26,4)</th>
<th>Q (26,3)</th>
<th>norm (27,5)</th>
<th>sqrt() (23,3)</th>
<th>div() (21,3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSD alg. (W,I)</td>
<td>(\hat{y}) (10,4)</td>
<td>R (9,3)</td>
<td>(\Omega) (8,1)</td>
<td>(b_i(s)) (12,5)</td>
<td>(d(s)) (10,5)</td>
<td></td>
</tr>
<tr>
<td>LLR (W,I)</td>
<td>(\sigma) (8,0)</td>
<td>LLR (10,5)</td>
<td>(L_D(b_k)) (6,4)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE II
THE DEVICE UTILIZATION FOR XILINX VIRTEX-IV CHIP AND LATENCIES.

<table>
<thead>
<tr>
<th>Resource</th>
<th>SQRD</th>
<th>LSD alg.</th>
<th>LLR calc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slices</td>
<td>2848</td>
<td>1595</td>
<td>1841</td>
</tr>
<tr>
<td>BRAMs</td>
<td>2</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>DSP48s</td>
<td>24</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Latency</td>
<td>9.06(\mu s)</td>
<td>0.133(\mu s \cdot D)</td>
<td>0.212(\mu s)</td>
</tr>
<tr>
<td>Throughput</td>
<td>110k oper./s</td>
<td>13.3Mbps@19dB</td>
<td>75.5Mbps</td>
</tr>
</tbody>
</table>
Summary and Conclusions

- List sphere detector (LSD) is an enhancement of SD that can be used to approximate the optimal soft output MAP detector in MIMO-OFDM systems
  - The LSD provides a tradeoff between the performance and the computational complexity depending on the list size
  - The detection of the signal has to done separately for each subcarrier in MIMO-OFDM system
- Modifications should be done for LSD for efficient implementation
  - Real signal model
  - Limited tree search
  - LLR clipping
- Implementation of IR-LSD presented
  - Architecture examples
  - FPGA implementation results
  ➔ LSD feasible for practical systems
References


Thank you!
Questions? Comments?