Low-Complexity LDPC-coded Iterative MIMO Receiver Based on Belief Propagation algorithm for Detection

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Outline

- Introduction
- System description
- Joint Factor Graph representation and shuffle schedule
- Proposed low complexity MIMO-BP detection
- Simulations results and Conclusions
I – Introduction : MIMO

- Improved throughput
- Iterative receivers including a MIMO detector
  - Better performance
  - Few implementations due to high computational complexity and latency => costly iterative process.

A detection principle based on the Belief Propagation (BP) algorithm was chosen as a solution to tackle these drawbacks.
II - Introduction: Non-Binary LDPC codes

- Proposed in 1998 by Davey and Mackay.
- Reduced-complexity decoding via Extended Min-Sum algorithm [Decl07].
- Improved performance for short and medium frame lengths.
- Convenient combination with high-order modulation and multiple antenna schemes.

In this work, a low-complexity BP-based layered detection and decoding for NB-LDPC Coded MIMO system is studied.
The source information is encoded by a NB-LDPC encoder.

Then, log2(q) bits are mapped to a complex symbol of a QAM constellation.

After a serial to parallel conversion, these symbols are spatially multiplexed onto a multiple antenna system and then transmitted over a MIMO channel.

At the receiver side, a MIMO-BP detection and an NB-LDPC decoding can be combined together to form a larger JFG where extrinsic information is exchanged.
Joint Factor Graph representation

- Upper part: factor graph representation of the MIMO SM detector.
- Lower part: factor graph representation of the parity matrix of the NB-LDPC decoder.
- A MIMO SM having two antennas considered: perform the MIMO detection over couples of received observations.
Iterative MIMO-BP detector

The factor graph of the MIMO-BP detection for the first couple of symbols

After several iterations
MIMO 2X2 system => we propose to perform the MIMO detection over couples of received observations.

Every couple of variable nodes is processed independently. Connected check nodes are updated then extrinsic information can become available again at variable node level.

Late symbols in a frame can profit from detector (candidate symbols) and decoder (check node) updates thanks to the schedule.

Extrinsic information can be exchanged between the decoder output and the MIMO detector input before the end of one complete inter-iteration.
Low complexity Receiver

- **Goal**
  - Reduce the overall complexity of the iterative receiver

- **Proposal**
  - Reduce complexity of the Euclidean distance computation
    - Reduce the number of computations in signal space
    - Reduced complexity computation via recursive steps
  
  - Reduce complexity of the iterative steps by lowering the number of exchanged messages
Reduced-complexity Euclidean distance computation

- MIMO 2X2 with 64-QAM S1 and S2 symbols
- Perfect CSI is assumed

Applied steps
- Conditioned detection on one symbol S1 (resp. S2), i.e., replace in Euclidean distance by the chosen value
- For the other symbol S2 (resp. S1) choose a subset of the 64-QAM constellation based on the sign of the received real I and Q components of the symbol
Reduced complexity Euclidean distance computation (step 1)

- Subset should include constellation points to allow for a soft detection (closest symbol with opposite bit value for all bits in a symbol)

- Compute Euclidean distance of the points in the subset (Step 2)

- Reduction to 25 Distance computations

- Repeat the steps for all conditioned values of S1 (resp. S2)
Reduced complexity Euclidean distance computation (Step 2)

- **Reduced complexity computation:**
  - Compute the Euclidean distance between the received observation and one corner constellation point of the subset region

\[
D_{Euc}^2 = \left| D_{Euc}^I \right|^2 + \left| D_{Euc}^Q \right|^2 = f(h_{i,i}^I, h_{j,i}^Q, S_1^I, S_1^Q, S_2^I, S_2^Q, y_1, y_2)
\]
Reducing the number of exchanged messages

Extended Min-Sum Algorithm

⇒ Ordered LLR values in increasing reliability order at input and output
⇒ Limitation to $n_m$ most reliable symbol reliabilities
⇒ $n_m$ S1 and S2 symbol reliabilities (instead of 64) available at output of decoder

Extrinsic updates from LDPC output ⇒ Update S1 symbol with S2 symbol reliability and vice-versa
Proposed low complexity MIMO-BP detection

- Structure and the Compensation of the truncated vectors

The $n_m$ most reliable vectors of the extrinsic information feedback from the decoder at the $t^{th}$ iteration

- The $n_v$ most reliable vectors from the decoder
- The $n_c$ most reliable vectors of Euclidean distances in the detector

Compensated part 64- ($n_c + n_v$)
Computational complexity and EXIT chart analysis

EXIT chart analysis is used to reveal the best parameters for the low complexity detector and the best profile of iterations for the receiver.

<table>
<thead>
<tr>
<th>Nb. Of Operations per iteration</th>
<th>Nb. Of additions</th>
<th>Nb. Of comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_c = n_v = 2$ $n_m = 6$</td>
<td>168</td>
<td>1328</td>
</tr>
<tr>
<td>$n_c = n_v = 2$ $n_m = 8$</td>
<td>184</td>
<td>1600</td>
</tr>
<tr>
<td>$n_c = n_v = 3$ $n_m = 6$</td>
<td>188</td>
<td>1608</td>
</tr>
<tr>
<td>$n_c = n_v = 3$ $n_m = 8$</td>
<td>212</td>
<td>1888</td>
</tr>
<tr>
<td>Full – BP</td>
<td>8192</td>
<td>8192</td>
</tr>
</tbody>
</table>
Simulation parameters

- **Simulations to show**
  - BP detection penalty
  - Performance improvement of iterative receiver
  - Symbol-based processing gain
  - Reduced complexity receiver penalty

- **Simulation conditions**
  - NB-LDPC code defined in [Voici08] over GF(64)
  - WiMax LDPC
  - 64-QAM constellation
  - Rayleigh fading channel
  - Frame size of N=384 QAM symbols (N=2304 bits)
  - Code rate R=1/2
- **NDD**: number of global iterations on JFG
- **det**: number of detector iteration per NDD
- **dec**: number of decoder iteration per NDD

Simulation results (1/2)

![Graph showing BER vs SNR for different receiver types and penalties](image)

- Iterative receiver BP detection penalty
- Non-iterative receiver BP detection penalty

Bit to Symbol gain
- \( n_c \): number of considered detector reliabilities
- \( n_v \): number of considered LDPC decoder reliabilities
- \( n_m \): number of EMS decoding reliabilities and exchanged extrinsic symbol information

- Applying the proposed low-complexity BP-based detection greatly reduces the number of operations per iteration with a negligible performance penalty.
Conclusion

- In this paper, the combination of a symbol-based MIMO detector with an NB-LDPC decoder is investigated.

- A joint factor graph representation of the MIMO SM and the NB-LDPC code enables a joint BP-based detection and decoding.

- Applying the proposed low-complexity BP-based detection greatly reduces the number of operations per iteration with a negligible performance penalty.

- EXIT chart analysis is used to reveal the best parameters for the low complexity detector and the best profile of iterations for the receiver.

- Results show a division by a factor of ten the number of operations in the detector for each inter-iteration between the detector and the decoder when compared to full-complexity BP.

- The penalty of introducing sub-optimal BP-based detection is greatly reduced when iterative processing is applied between the detector and the decoder.