Abstract—Requirements for higher data rates and lower power consumption set new challenges for implementation of multiple-input multiple-output orthogonal frequency division multiplexing (MIMO–OFDM) receivers. Simple detectors have the advantage of low complexity and power consumption, but they cannot offer as good performance as more complex detectors. Therefore it would be beneficial to be able to adapt the detector algorithm to suit the channel conditions to minimize the receiver processing power consumption while satisfying the quality of service requirements. At low signal-to-noise ratio (SNR) and/or low rank channel, more power and computation resources could be used for detection in order to guarantee reliable communication, while in good conditions, a simple and less power consuming detector could be used.

In this paper, we compare the performance of different detection algorithms. The performance results are based on simulations in long term evolution (LTE) system. The effect of precoding and hybrid automatic repeat request (HARQ) on the performance is shown. Implementation results based on the existing literature are included in the comparison. We discuss when it would be beneficial to use a complex detector and when a simple one would be sufficient. Also the switching criterion is discussed.

I. INTRODUCTION

The third generation (3G) long term evolution (LTE) standard uses a combination of multiple-input (MIMO) and orthogonal frequency division multiplexing (OFDM) to offer better performance in terms of capacity, diversity and bandwidth efficiency [1]. The receivers for MIMO–OFDM systems need to be capable to cope with interference caused by spatial multiplexing or inter-antenna interference. The challenge is to find efficient detection algorithms with high detection rate, low computational complexity and low power consumption. Even if the hardware detection rate of a low-complexity detector is high, poor channel conditions may impair the overall performance of the detector and a more complex receiver is required to reach the data rate requirements.

Linear minimum mean-square error (LMMSE) detector can straightforwardly be applied in MIMO detection, but the performance degrades significantly in fading channels, especially in high correlated scenarios [2]. In order to fight the interference caused by multiple antennas, the successive interference cancellation (SIC) has been proposed [3]. In this approach the strongest signal is detected first and its interference is cancelled from the other received signals, instead of jointly detecting the signals from all the antennas. The detection and cancelling are done in a serial fashion so that after the strongest signal is detected and cancelled, the second strongest signal is detected and cancelled from the remaining signals and so on. The detection of each layer can be performed with the LMMSE equalizer. Log-likelihood ratios (LLR) are calculated from the LMMSE equalizer outputs, deinterleaved and decoded and symbol expectations are computed. The expectations are then cancelled from the second layer. The LTE specification [1] includes vertical encoding for $2 \times 2$ and $4 \times 4$ MIMO system, where one encoded stream is mapped onto multiple layers. All of the detected layers have to be decoded before soft interference cancellation can be performed. Therefore the SIC algorithm is most suitable for horizontally encoded case, where detected layers can be decoded separately and the interference from the strongest layers can be cancelled from the other layers.

In addition to linear receivers, we have chosen to use $K$-best list sphere detector (LSD) [4] and selective spanning with fast enumeration (SSFE) [5] for MIMO detection. The $K$-best LSD and SSFE are both breadth-first tree-search algorithms [4], [5]. The $K$-best LSD keeps $K$ nodes with smallest accumulated Euclidean distances at each level of the tree. With the SSFE, at every level of the tree, the number of spans for each node is specified with the element of the spanning vector, $m$, corresponding to that level. The candidates of the SSFE are not deleted during the algorithm execution.

Adaptive detection for MIMO systems has been proposed in [6] where a channel metric is computed in order to choose between different detectors. The metric can be either the condition number of the channel or derived from the distribution of channel correlations. A low complexity detector is chosen when there is low correlation in the channel and a more complex detector is chosen for an ill-conditioned channel.

In [7], the receiver switches between maximum likelihood (ML) and LMMSE detection. The LMMSE is used for channels with high orthogonality whereas ML is used for channels with low orthogonality. The switching criterion is either the condition number or orthogonality deficiency of the channel and predetermined thresholds are used. It was shown that the proposed adaptive detection scheme provides a trade-off between the performance and complexity, but the complexity results were based on theory, not on actual implementations.

An adaptive MIMO detector including maximum ratio combining (MRC), LMMSE and SIC was implemented in [8]. Different modulation schemes and antenna configurations were supported. The authors provide implementation related results, but there are no results showing the performance of the algorithms on the system level. Also no attention was paid to the switching criterion.

The paper is organized as follows. The system model is presented in Section II. In Section III the performance comparison based on simulations are shown and implementation results found in literature are presented. In Section IV we discuss the adaptive detector and the theoretical complexities of the detectors as numbers of arithmetic operations. The conclusion are drawn in Section V.

II. SYSTEM MODEL

We consider an OFDM based MIMO transmission system using $N_T$ transmit and $N_R$ receive antennas, where $N_T \leq N_R$. A spatial multiplexing transmission where $N_S = \min(N_T, N_R)$ data streams are multiplexed over $N_T$ transmit antennas, is applied. Horizontal encoding is used, which means that two data streams are encoded separately and then mapped onto different layers. In the $4 \times 4$ MIMO system, each of the two streams are multiplexed onto two antennas. The first stream is multiplexed onto the first and second antenna and
the second stream onto the third and fourth antenna. The system model is illustrated in Fig. 1.

The received signal for each OFDM subcarrier \( k \) is given as

\[
y_k = H_k P x_k + \eta_k, \quad k = 1, 2, \ldots, K,
\]

where \( y_k \in \mathbb{C}^{N_t \times 1} \), \( x_k \in \mathbb{C}^{N_r \times 1} \), and \( \eta_k \in \mathbb{C}^{N_r \times 1} \) are the received signal, the transmitted signal, and the complex zero-mean Gaussian noise vector, respectively, for subcarrier \( k \). \( H_k \in \mathbb{C}^{N_t \times N_r} \) is the channel matrix for subcarrier \( k \) and \( P \in \mathbb{C}^{R \times N_r} \) is the precoding matrix with rank \( R \). The entries of \( x_k \) are chosen independently from a complex quadrature amplitude modulation (QAM) constellation.

Hybrid automatic repeat request (HARQ) [9], [10] based on Chase combining with maximum of one retransmission is used and an error-free feedback channel is assumed. LTE-Advanced (LTE-A) codebook based precoding [1] is considered. The precoding matrix \( P \) with the highest instantaneous mutual information value is chosen. It is calculated for 4th subcarrier as

\[
C_k = \log(\det(\mathbf{I} + \frac{E_s}{\sigma^2 N_t} (H_k P)^H H_k P)),
\]

where \( E_s \) is the symbol energy, \( \mathbf{I} \) is an identity matrix and \( \sigma^2 \) is the noise variance. Capacity is summed over the subcarriers in the frame.

III. PERFORMANCE AND IMPLEMENTATION COMPARISONS

A. Performance Comparison

The performance of different detector algorithms is compared in 4x4 MIMO-OFDM system in terms of transmission throughput. The throughput is defined as the nominal information transmission rate of successfully transmitted information bits times (1 - frame error rate (FER)). The number of transmitted frames is the same for simulations with and without HARQ. In the HARQ scheme, if the transmitted data is received erroneously, the erroneous packet is saved and retransmission of the same data is requested. The erroneous packet and the data from the retransmission are combined and decoded. The retransmission continues until the data is received successfully or the maximum number of retransmissions is reached. HARQ enables more reliable communication, but increases the latency of the system, because the transmitter sends one frame at a time and waits for an acknowledgement from the receiver before sending the next frame. In a system without HARQ, every frame contains different data. If the frame is received erroneously, it is discarded and new data is sent.

The simulation parameters are based on the LTE standard and the typical urban (TU) channel model is applied [11]. The simulation and channel model parameters are given in Table I.

Each signal-to-noise ratio (SNR) point corresponds to transmission of 1000 frames. Perfect channel state information was assumed at the receiver. The number of turbo decoder iterations was set to 8. The channel with base station (BS) azimuth spread of 5° is considered as a moderately correlated channel, and with 2° as a highly correlated channel.

The throughput of different detectors in a highly correlated channel is shown in Figs. 2 and 3 without and with precoding and HARQ, respectively. The dashed line in the figures represents the 4-QAM, the solid line the 16-QAM and the dash-dot line the 64-QAM modulation. The SSFE was simulated only for 16-QAM and 64-QAM. The spanning vector for SSFE is shown in the figures with the last value corresponding to the first level and the first value corresponding to the last level in the tree. The SSFE list size was 24 for the highly correlated channel.

The use of HARQ and precoding increases throughput on the lower SNR regime and the effect is clearly seen especially for the 4-QAM case. Also the difference between LMMSE and SIC is decreased and on some occasions, LMMSE produces better throughput than SIC. However, precoding and HARQ do not enhance the performance of LMMSE and SIC enough to exceed the 8-best and SSFE detectors. If the maximum number of retransmissions for HARQ was increased to 2, the LMMSE would outperform other detectors at the lower SNR regime for 16-QAM.

Similar behavior can also be seen for the moderately correlated channel. In Figs. 4 and 5, the throughput in a moderately correlated channel is presented for transmission without and with HARQ and precoding, respectively. The SSFE list size was 8 for the moderately correlated channel and the used spanning vector is shown in the figures.

The use of HARQ and precoding clearly increases throughput at the lower SNR regime where the LMMSE outperforms other detection algorithms, as could be expected based on numerous earlier studies. If more retransmissions were allowed to be used, throughput could be further increased, but the impact will saturate.

In the simulations herein, the precoding matrix was chosen based on the instantaneous capacity. It was noticed that when using precoding without HARQ, the performance was sometimes even worse than transmitting without precoding and HARQ. This indicates that capacity is not the most suitable method for choosing the precoding matrix and another method should be found.

B. Implementation Comparison

The implementation comparison was done based on the results found in literature.

1) Complexity and Power Consumption: In [12], it was shown that LMMSE, SIC and K-best LSD have complexities and power consumptions close to each other when the modulation order is low (4-QAM). The complexity and power consumption of the K-best LSD grow with the modulation order whereas the LMMSE and SIC detectors have similar complexities and power consumption levels on all modulation orders. The SSFE and the 8-best LSD were compared in [13] and it was found that the 8-best has lower complexity and
power consumption with 16-QAM, but with 64-QAM the algorithms have similar complexity and power consumption. The detection rate of the SSFE algorithm is higher than that of the K-best for both modulation orders.

In the K-best algorithm, a large list size improves the performance [12] but increases the computational complexity. Because the modulation order and list size have an impact on the complexity and power consumption of the K-best algorithm, it would be beneficial to also adapt the modulation order and coding rate to achieve lower power consumption. This would mean that in channel conditions where a K-best detector would be chosen, instead of using a modulation and coding scheme (MCS) with 64-QAM, the transmitter would find a MCS with lower modulation order which achieves similar performance as the one with 64-QAM. This way the detector’s power consumption could be decreased without degrading the performance.

2) Latency: A 0.5-ms slot is allocated for 7 or 6 OFDM symbols depending on the cyclic prefix length [1]. It is shown that the LMMSE detector is fast enough for 4 × 4 MIMO and all modulation cases [12] when 20 MHz bandwidth is used. Also the SIC detector is fast enough when implemented on application-specific integrated circuit (ASIC). The ASIC implementation of the K-best for 4 × 4 MIMO does not meet the requirements only when 64-QAM is used or in the case of 16-QAM with list size 16. The most time consuming blocks in the implementations of the detectors are the QR decomposition, LMMSE and K-best for higher order modulations [12].

3) Goodput: The goodput is defined as the minimum of the hardware detection rate times the code rate and the reliable transmission throughput [12]. Precoding and HARQ are not taken into account in the following results.

The detection rate of the LMMSE and SIC receivers is high compared to the 8-best LSD [13], but when the SNR is low or the channel is spatially correlated, the reliable transmission throughput is degraded. In channels with no correlation, the LMMSE and SIC detectors give the best goodput [14]. When spatial correlation is introduced, the 8-best LSD gives the highest goodput. The K-best LSD is capable of receiving data reliably from higher distances than the SIC or LMMSE with a fixed transmit power [12]. The SSFE was noted to perform well in moderately correlated channel, but K-best...
LSD is needed for highly correlated channels [14].

IV. ADAPTIVE DETECTOR

An optimal receiver would be able to adapt to varying channel conditions by changing the detection algorithm. Also the modulation and coding rate could be adapted. The adaptive detector should be designed in a way that different detection algorithms could utilize the same blocks for computations and the blocks not used at the moment could be switched off but also switched on fast enough. For example, the LMMSE filter could be computed using the QR decomposition, which is also used as preprocessing for K-best LSD and therefore the same QR decomposition block could be used by both detection algorithms.

The implementation results found in the literature showed that even though the LMMSE equalizer has a high detection rate, the goodput is poor in difficult channel conditions, and thus, a simple receiver is most suitable for uncorrelated channels. Our simulations with precoding and HARQ showed that it could be possible to use the LMMSE algorithm also in a moderately correlated channels at the lower SNR regime, whereas in highly correlated channels, the K-best is still the most reliable detector. Also, a high SNR would enable the use of a simple detector in highly correlated channels, but such scenarios may not be realistic.

The theoretical complexities of the detectors as numbers of arithmetic operations for 4 × 4 antenna system with moderate correlation are presented in Table II. The LMMSE filter was computed using extended channel matrix and QR decomposition. The operation counts for K-best and SSFE algorithms include also preprocessing using QR decomposition and LLR calculation. The LMMSE and SIC detectors include LLR computation and in the case of SIC algorithm, also computation of symbol expectations. The SIC algorithm includes 2 iterations, decoding is not included in the operation counts.

The SSFE algorithm is the least complex in terms of multiplications and additions, but requires more comparison operations than the LMMSE and SIC algorithms. The K-best is the most complex detector, but it delivers the highest throughput. The LMMSE and SIC detectors are affected by the modulation order in the LLR and symbol expectation calculation and therefore the difference between different modulation orders is small. The complexity of the K-best and SSFE algorithms grows with modulation order and list size. In highly correlated scenarios the SSFE algorithm requires larger list size to perform as well as the K-best, which increases the complexity of the SSFE.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Modulation</th>
<th>Multiplications</th>
<th>Additions</th>
<th>Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMMSE</td>
<td>16-QAM</td>
<td>1528</td>
<td>1742</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>64-QAM</td>
<td>1900</td>
<td>1932</td>
<td>80</td>
</tr>
<tr>
<td>SIC 2 at</td>
<td>16-QAM</td>
<td>2120</td>
<td>1512</td>
<td>256</td>
</tr>
<tr>
<td></td>
<td>64-QAM</td>
<td>2236</td>
<td>1900</td>
<td>48</td>
</tr>
<tr>
<td>8-best</td>
<td>16-QAM</td>
<td>2528</td>
<td>2340</td>
<td>3609</td>
</tr>
<tr>
<td></td>
<td>64-QAM</td>
<td>3528</td>
<td>3510</td>
<td>10270</td>
</tr>
<tr>
<td>SSFE [1,1,1,1,2,2,2]</td>
<td>16-QAM</td>
<td>1048</td>
<td>1500</td>
<td>537</td>
</tr>
<tr>
<td></td>
<td>64-QAM</td>
<td>1048</td>
<td>1508</td>
<td>687</td>
</tr>
<tr>
<td></td>
<td>2560</td>
<td>2122</td>
<td>1734</td>
<td></td>
</tr>
</tbody>
</table>

The criteria of when to switch from a simple detector to a more complex one is an open issue. The use of condition number of the channel [6], [7], distribution of channel correlation [6] and orthogonality deficiency of the channel [7] have been proposed. In addition to these, also some simple metric, such as capacity, could be considered. The metric should be able to supply information about the spatial characteristics and power levels of the channel. The computation of detector switching criterion should be included in the implementation of the adaptive detector since it will affect the power consumption and complexity.

V. CONCLUSIONS

In this paper, we presented a comparison between different detector algorithms in terms of transmission throughput. Complexity and power consumption results from the literature were included in the comparison together with theoretical complexities as numbers of arithmetic operations. With HARQ and precoding, a simple LMMSE or SIC detector could be used in moderately correlated channels at lower SNR regime, otherwise they perform best in an uncorrelated channel. The SSFE could be used in channels with moderate correlation, but in highly correlated channels the K-best LSD should be used to guarantee reliable communication.

This study served as a basis for implementation of an adaptive detector, where the detection algorithm is adapted to suit the channel conditions in order to achieve power savings. In the future also channel estimation will be added to the design and its effect on the goodput will be studied.

REFERENCES