Detection and Channel Estimation in 8×8 MIMO-OFDM

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***Abstract*—Higher data rate and lower power consumption requirements set new challenges for implementation of multiple-input multiple-output orthogonal frequency division multiplexing (MIMO–OFDM) receivers. Simple detectors have low complexity and power consumption, but the performance is worse than with more complex detectors. Therefore the detector can be adapted to suit the channel conditions to minimize the power consumption while satisfying the quality of service requirements.**

The performances of the linear minimum mean-square error (LMMSE) detector and the K-best list sphere detector (LSD) in a long term evolution (LTE) system are compared. We also investigate least squares (LS) channel estimation performance with different mobile speeds and correlation scenarios. Theoretical complexities of the detectors are also given. In the 4×4 system, high order modulation and bad channel estimate impacts the performance of the K-best detector, resulting it to be outperformed by the LMMSE detector. In the 8×8 case, the K-best LSD outperforms the LMMSE detector, since the channel conditions are more challenging for the LMMSE detector.

I. Introduction

The third generation partnership project (3GPP) 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.

A linear minimum mean-square error (LMMSE) detector can be straightforwardly applied to MIMO detection, but the performance degrades significantly in fading channels, especially in high correlation scenarios [2]. In addition to a linear receiver, we have chosen to use the K-best list sphere detector (LSD) [3] for MIMO detection. The K-best LSD is a breadth-first tree-search algorithm [3], [4], which keeps K nodes with the smallest accumulated Euclidean distances at each level of the tree.

Adaptive detection for MIMO systems has been proposed in [5], 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 [6], the receiver switches between maximum likelihood (ML) and LMMSE detection. 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.An adaptive MIMO detector including maximum ratio combining (MRC), LMMSE and SIC was implemented in [7]. 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.

Channel estimation for 4×4 MIMO-OFDM systems with the LTE pilot structure has been widely studied [8]–[10], but there are very few papers considering channel estimation in 8×8 MIMO-OFDM systems. Channel estimation algorithms for LTE-Advanced (LTE-A) reference signal structure were investigated in [11], including least squares (LS) and minimum mean square error (MMSE) estimation. However, simulation results were only provided for 4×4 case.

By adapting the detector to current channel conditions, highest throughput performance with lowest possible power consumption can be achieved. This becomes increasingly important in cognitive radio transceivers, where the channels are changed frequently based on availability. In this paper, the LMMSE and K-best detectors are compared in terms of performance and complexity with known and estimated channels. Results are presented for both 4×4 and 8×8 systems. The theoretical complexities of the detectors are given in terms of the numbers of arithmetic operations to give an insight into the implementation complexities of the detectors and factors affecting them. The LTE pilot structure and hybrid automatic repeat request (HARQ) are used for obtaining results applicable to practical systems. The outcome gives guidelines for detector adaptation by presenting simulation and theoretical complexity results.

The paper is organized as follows. The system model is presented in Section II. In Section III the performance comparison based on simulations is shown for 4×4 and 8×8 MIMO. In Section IV we discuss the adaptive receiver. 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. The system model is illustrated in Fig. 1.

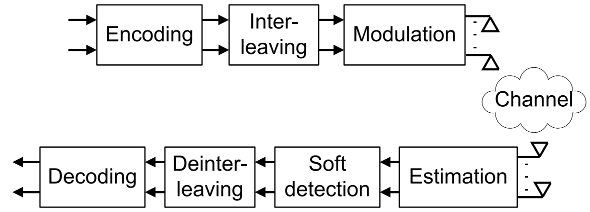

Fig. 1. System model.

The received signal for each OFDM subcarrier p is given as

$$\mathbf{y}_p = \mathbf{H}_p \mathbf{x}_p + \eta_p, p = 1, 2, ..., P, \tag{1}$$

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where $\mathbf{y}_p \in \mathbb{C}^{N_R \times 1}$, $\mathbf{x}_p \in \mathbb{C}^{N_T \times 1}$, and $\eta_p \in \mathbb{C}^{N_R \times 1}$ are the received signal, the transmitted signal, and the complex zero-mean Gaussian noise vector, respectively, for subcarrier p. $\mathbf{H}_p \in \mathbb{C}^{N_R \times N_T}$ is the channel matrix for subcarrier p. The entries of $\mathbf{x}_p$ are chosen independently from a complex quadrature amplitude modulation (QAM) constellation. P is the number of subcarriers. HARQ [12], [13] based on Chase combining with maximum of 3 retransmission is used and an error-free feedback channel is assumed.

A. Channel Estimation

We assume pilot aided transmission, where pilot symbols known at the receiver are used to estimate the channel [14], [15].

For 4×4 transmission, the cell-specific reference signals (CRS) are transmitted in a resource element grid as in LTE [1] and shown in Fig. 2. Quadrature phase shift keying (QPSK) modulated pilot symbols are assumed. The channel estimates from the pilot symbols are obtained with LS estimator, which aims at minimizing the squared difference between the known pilot symbols and the received signal [16]. Before the estimation, the received signal is transformed into frequency domain with fast Fourier transform (FFT). After estimation, the channel impulse response result is transformed into frequency domain using a second FFT. The length of the channel and the tap delays are assumed to be known.

For 8×8 transmission, the demodulation reference signals (DM-RS, also known as UE-specific RS) are used, as depicted in Fig. 2. The pilots are orthogonalized using a combination of frequency division multiplexing (FDM) and code division multiplexing (CDM), which is accomplished by applying spreading codes over time domain. [17] At the receiver side, each pilot is decoded using the same spreading code as was used in encoding. This results in the reference signal being spread over four resource elements in time domain and therefore we cannot perform decoding and estimation until the whole subframe or transmission time interval (TTI) is received. The LS estimator proposed in [11] is used here for the 8×8 channel estimation.

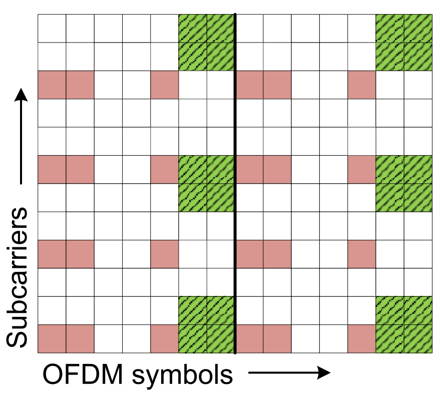

Fig. 2. The LTE pilot structure over one TTI [1].

III. Performance Comparison

A. Simulation Setup and Parameters

The performance of the LMMSE and K-best LSD algorithms is compared in 4×4 and 8×8 MIMO–OFDM systems 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)). Here one frame is considered as one TTI. If there is even one erroneous symbol in the TTI, the whole TTI is discarded.

TABLE I
Simulation and Channel Model Parameters

Simulation parameters	
Coding	Turbo coding with 1/2 code rate
Number of subcarriers	512 (300 used)
Bandwidth	5 MHz
Symbol duration	71.4 μs
Duration of one TTI	14 OFDM symbols
Modulation	4-QAM, 16-QAM and 64-QAM
Channel model	TU vehicular A
Channel model parameters	
Number of paths	6
Path delays	[0...2510] ns
Path power	[0...-20] dB
BS antenna spacing	4 λ
MS antenna spacing	0.5 λ
BS average angle of departure	20°
MS average angle of arrival	67.5°
BS azimuth spread	2° / 5°
MS azimuth spread	35°

The number of transmitted symbols 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 packet at a time and waits for an acknowledgement from the receiver before sending the next packet. In a system without HARQ, every packet contains different data. If the packet 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 [18]. The simulation and channel model parameters are given in Table I.

Each signal-to-noise ratio (SNR) point corresponds to transmission of 6720 OFDM symbols when the mobile speed is 3 km/h. 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.

B. 4×4 MIMO

The performance of the LMMSE and K-best LSD with list sizes of 8 and 16 in a moderately correlated channel is shown in Fig. 3 with perfect CSI and in Figs. 4 and 5 with LS channel estimation with different speeds. For the sake of clarity, the 4-QAM and 64-QAM modulation schemes are plotted in Fig. 4 whereas the 16-QAM is shown in Fig. 5. It is clearly seen that as the modulation order and mobile speed grow, the channel estimation performance degrades and the difference between the performance of different detectors decreases. With higher order modulations and higher mobile speeds, the LMMSE detector is able to outperform the K-best detector as can be seen in Figs. 4 and 5.

The performances of the detectors in a highly correlated channel with perfect CSI are shown in Fig. 6 and with LS channel estimation in Figs. 7 and 8. In a highly correlated channel, the performance of the LMMSE receiver suffers as depicted. The effect of increasing correlation on the LS channel estimation can be observed by comparing Figs. 4, 5, 7 and 8. With the LMMSE detector, the performance of

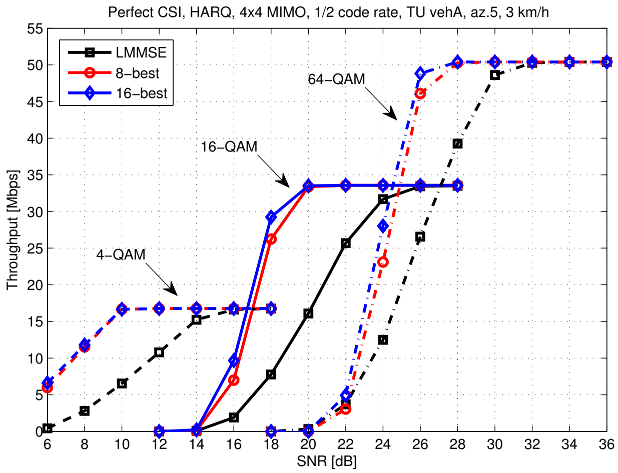

Fig. 3. Data transmission throughput vs. SNR in a moderately correlated channel with perfect CSI.

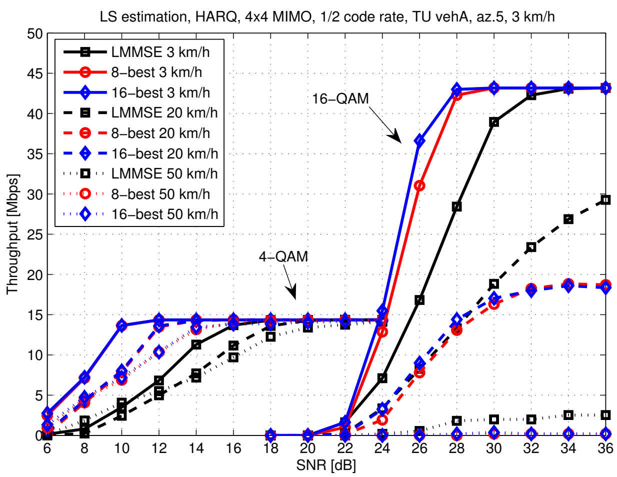

Fig. 4. Data transmission throughput vs. SNR in a moderately correlated channel with channel estimation for different mobile speeds.

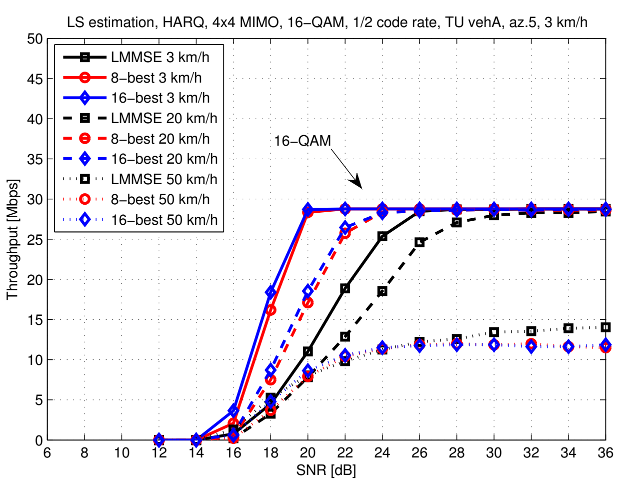

Fig. 5. Data transmission throughput vs. SNR in a moderately correlated channel with 16-QAM and channel estimation for different mobile speeds.

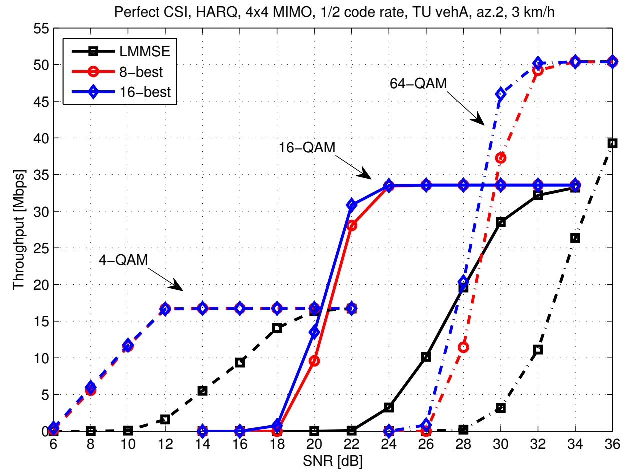

Fig. 6. Data transmission throughput vs. SNR in a highly correlated channel with perfect CSI.

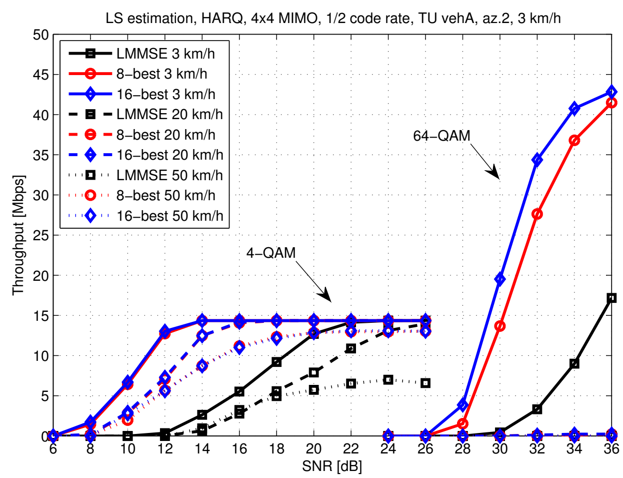

Fig. 7. Data transmission throughput vs. SNR in a highly correlated channel with channel estimation for different speeds.

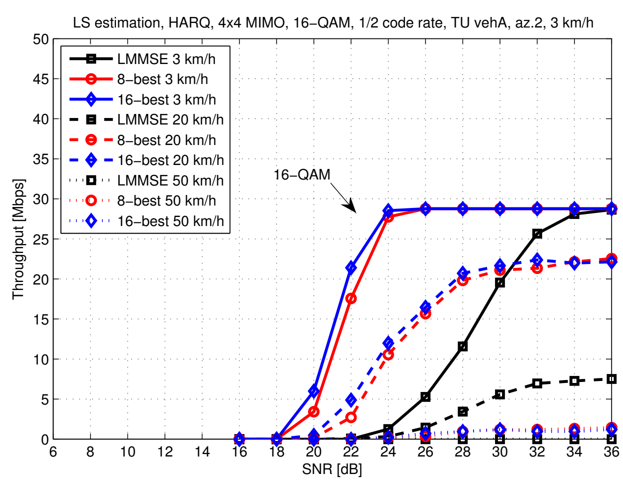

Fig. 8. Data transmission throughput vs. SNR in a highly correlated channel with 16-QAM and channel estimation for different speeds.

the LS estimator is poor, especially when the modulation order and mobile speed increase. Also with the K-best detectors the channel estimation performance is poor with higher modulation orders and mobile speeds when compared to the moderately correlated channel.

For example, the difference between moderately and highly correlated channels at 50 km/h mobile speed, 16-QAM modulation scheme and K-best detector is almost 15 Mbps.

C. 8×8 MIMO

The performance of the LMMSE and K-best LSD with list sizes of 8 and 16 in a moderately correlated channel is shown in Fig. 9 with perfect CSI and in Fig. 10 with LS channel estimation.

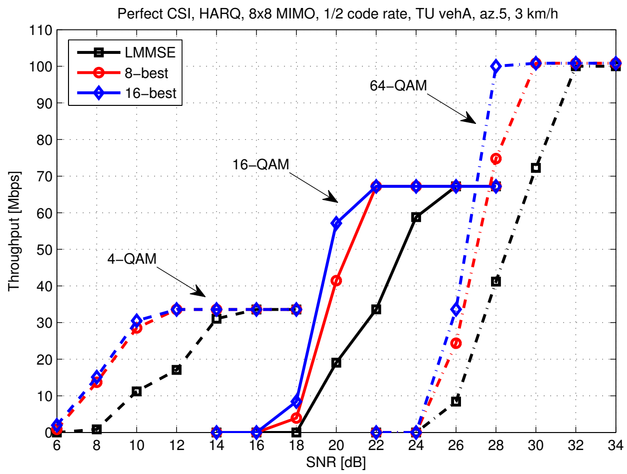

Fig. 9. Data transmission throughput vs. SNR in a moderately correlated channel with perfect CSI.

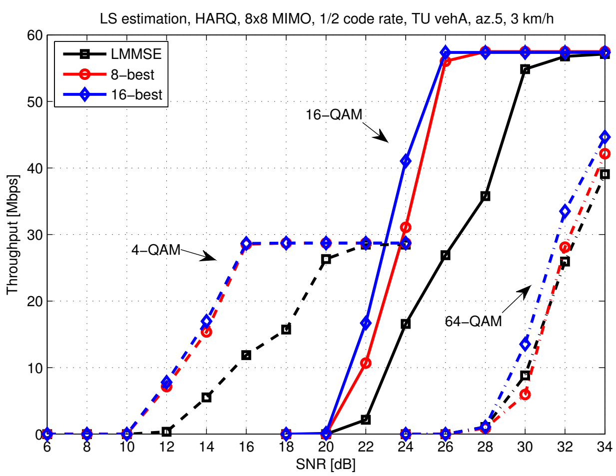

Fig. 10. Data transmission throughput vs. SNR in a moderately correlated channel with channel estimation.

The K-best detector is clearly outperforming the simple LMMSE detector, except in the case of 64-QAM and channel estimation. It should be noted that in the 4×4 MIMO system, the performance of the LS channel estimation at the speed of 3 km/h is similar to performance with perfect CSI, whereas in the 8×8 MIMO system this is not the case. In the 4×4 system the channel estimation is performed when a new pilot symbols is received and between the pilot symbols, the estimate is kept constant. This means that we get six estimates of the channel during one TTI. In the 8×8 system the estimation is performed after the whole TTI is received, as explained in Section II-A, and this results in only one channel estimate per TTI. Also for this reason, the mobile speed has a great effect on the channel estimation performance in the 8×8 system. If the mobile

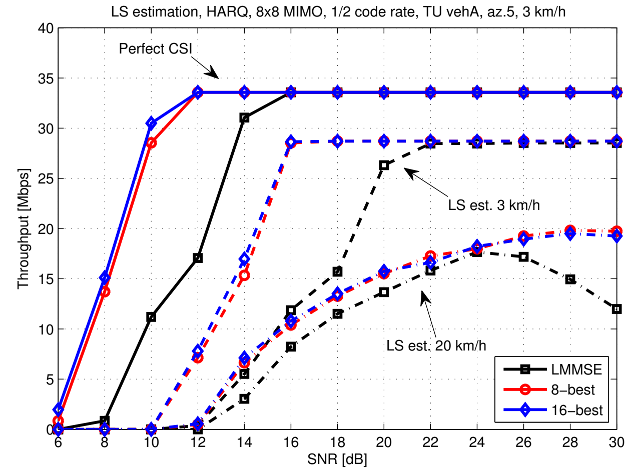

Fig. 11. Data transmission throughput vs. SNR in a moderately correlated channel with 4-QAM and channel estimation.

speed was increased to 20 km/h, only the 4-QAM modulation scheme would be able to provide throughput, as shown in Fig. 11, the two higher modulation schemes result in no throughput at all. With the speed of 50 km/h, the channel estimation fails to deliver error free TTIs resulting in zero throughput with all modulation schemes.

If the correlation is increased, the channel conditions become very challenging for the LMMSE detector as depicted in Fig. 12. The performance of the LMMSE detector is far from that of the K-best LSD in a highly correlated channel compared to the moderately correlated channel. Also the channel estimation performance suffers in highly correlated channels as shown in Fig. 13. The K-best detectors can offer throughput, but the LMMSE is performing poorly. When the 64-QAM modulation scheme is used, there is no throughput even at 38 dB SNR.

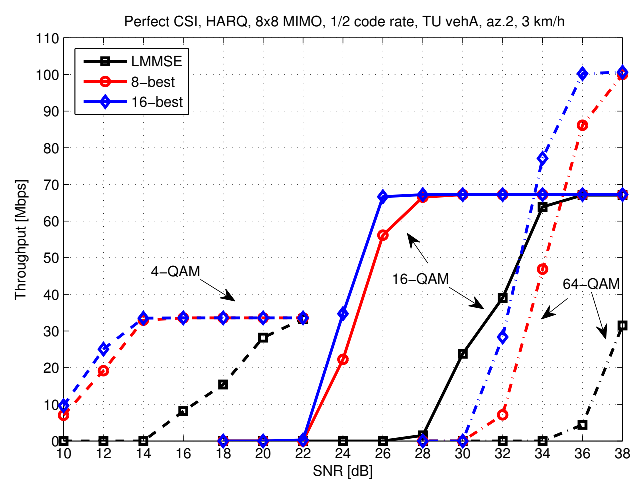

Fig. 12. Data transmission throughput vs. SNR in a highly correlated channel with perfect CSI.

D. Theoretical Complexities

The theoretical complexities of the detectors as numbers of arithmetic operations (multiplications, additions and comparisons) required to process on subcarrier are given in Table II. The LMMSE filter was computed using the $\mathbf{Q}$ and $\mathbf{R}$ matrices derived from the QR decomposition of the extended channel matrix. The computation of

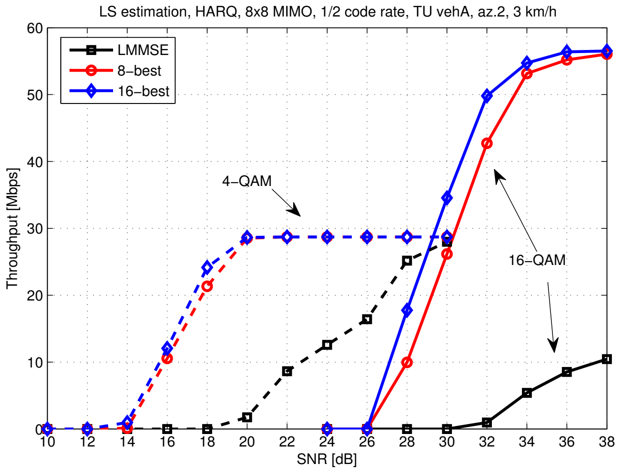

Fig. 13. Data transmission throughput vs. SNR in a highly correlated channel with channel estimation.

TABLE II
THEORETICAL COMPLEXITIES

Detector		Modulation	Mult.	Add.	Comp.
LMMSE	4x4	4-QAM	752	718	8
		16-QAM	776	720	32
		64-QAM	808	722	80
	8x8	4-QAM	5728	5596	16
		16-QAM	5776	5600	64
		64-QAM	5840	5604	160
8-best	4x4	4-QAM	872	808	1280
		16-QAM	1568	1392	3585
		64-QAM	2968	2552	10612
	8x8	4-QAM	3368	3184	2974
		16-QAM	5792	5376	8328
		64-QAM	10648	9744	22292
16-best	4x4	4-QAM	1360	1224	3000
		16-QAM	2824	2448	8559
		64-QAM	5472	4664	23269
	8x8	4-QAM	5674	5200	7368
		16-QAM	10504	9632	20125
		64-QAM	20064	18256	52583

the log-likelihood ratios (LLR) is included in the numbers. Because the same QR decomposition block can be used for both detector algorithms, the complexity of the QR decomposition is not included.

It is clearly seen that the K-best LSD requires more arithmetic operations than the LMMSE and is therefore more complex. The increasing modulation order together with the list size and antenna configuration has a great impact on the complexity of the K-best detector, whereas the complexity of the LMMSE detector is mostly affected by the number of antennas.

IV. Adaptive Receiver

An optimal receiver would be able to adapt to varying channel conditions by changing the detection and channel estimation 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.

As the simulation results showed, the list size of the K-best LSD does not affect the performance significantly when using the 4-QAM modulation scheme. Also with higher modulation orders the difference between list sizes of 8 and 16 is rather small, when channel estimation is used. Therefore in realistic communication systems where the perfect CSI is not available and computation resources are limited, the list size of 8 is adequate and adaptation of the list size to the channel conditions is unnecessary.

In difficult channel conditions with high or even moderate correlation, the performance of the LMMSE suffers due to the fact that it is not able to separate the MIMO streams. Therefore a more complex detector, such as the K-best LSD, is needed to ensure reliable communications.

In [19] we have studied the effect of precoding and HARQ on the performance of the LMMSE and 8-best LSD detectors when perfect CSI is available in a 4×4 MIMO system. The results show that if precoding is applied, the LMMSE could achieve similar or better performance than the 8-best LSD on some occasions in the moderately correlated channel. The results presented in this paper for the 4×4 MIMO show similar behavior when LS estimation is used with the higher modulation orders and mobile speeds. This indicates that fast fading moderately correlated scenarios, the LMMSE detection could be used instead of K-best LSD to reduce complexity.

With the 8×8 MIMO, the LMMSE is not able to deliver similar performance as the K-best LSD, especially when the correlation is high. With channel estimation, moderate correlation and 64-QAM, the LMMSE reaches the throughput of the K-best algorithm, which is similar to the 4×4 MIMO. However, if the mobile speed is increased, the LS estimator is not able to estimate all the channel variations, resulting in no throughput at all. Therefore a better estimator is needed to see if also with the 8×8 MIMO, the fast fading, moderately correlated scenarios would be the situations to choose the LMMSE over K-best LSD.

Also the channel estimation algorithm could be adapted. In a slowly fading channel a simple estimator, such as LS, could be used, whereas a fast fading scenario would require additional MMSE filtering of the channel estimates or a more complex channel estimation algorithm. Especially with the 8×8 MIMO, the performance with channel estimation is significantly decreased as the mobile speed increases, and a better estimator is needed.

V. Conclusions

In this paper, we presented a comparison between LMMSE and K-best LSD algorithms in terms of transmission throughput and showed the performance of the LS channel estimation on different mobile speeds in 4×4 and 8×8 MIMO-OFDM systems. The theoretical complexities of the detector algorithms were also given for different modulation schemes.

The simulation results in the 4×4 MIMO system showed that in highly correlated channels the LMMSE detector is unable to deliver similar throughput as the K-best LSD, as was expected. In moderately correlated channels, the difference between the detectors is decreased, and when channel estimation is used, the LMMSE can outperform the K-best LSD with higher modulation orders and mobile speeds. In the 8×8 MIMO system, the LMMSE detector is unable to separate all the MIMO streams and therefore the K-best LSD is outperforming LMMSE.

The theoretical complexities of the detectors show that the K-best LSD is significantly more complex than the LMMSE and therefore it would be beneficial to use the LMMSE in suitable channel conditions to save processing power. In addition of detector algorithm adaptation, the channel estimation algorithm could be adapted. In

4×4 MIMO system and slowly fading channels the LS estimation is sufficient, but increasing mobile speed requires more efficient estimation. Also the 8×8 MIMO requires better channel estimation even at low mobile speeds to provide higher throughput.

With perfect CSI the 4×4 MIMO system can offer better throughput than the 8×8 MIMO at the lower SNR regime, but the 8×8 MIMO results in higher throughput when the SNR increases. Similar behavior can be observed when LS channel estimation is used, as shown in Fig. 14 for 16-QAM and moderately correlated channel. With LS estimation, the difference between 4×4 and 8×8 MIMO is greater than with perfect CSI. This is due to the fact that the LS estimation alone is not adequate for 8×8 MIMO, and filtering or a more efficient channel estimation method is required, as stated before.

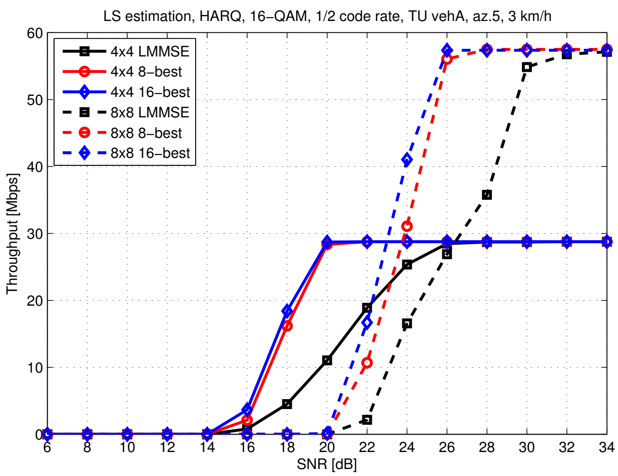

Fig. 14. Data transmission throughput vs. SNR in a moderately correlated channel with LS estimation and 16-QAM.

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