SIC AND K-BEST LSD RECEIVER IMPLEMENTATION FOR A MIMO-OFDM SYSTEM

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ABSTRACT

MIMO-OFDM receivers with horizontal encoding are considered in this paper. The successive interference cancellation (SIC) algorithm is compared to the K-best list sphere detector (LSD). The SIC and K-best LSD receivers are designed for a 2×2 antenna system with quadrature phase shift keying (QPSK),16-quadrature amplitude modulation (QAM) and 64-QAM. The linear minimum mean squared error (LMMSE) based SIC detector cancels decoder outputs from the received signal. The performance of the SIC algorithm depends on the channel conditions. The SIC algorithm performs worse than maximum *a posteriori* probability (MAP) and the K-best list sphere detectors (LSD) when the MIMO streams are highly correlated but the SIC receiver performs better than the K-best LSD with less correlated streams. However, the latency of the K-best LSD is higher than that of the SIC receiver.

1. INTRODUCTION

Multiple-input multiple-output (MIMO) systems offer an increase in capacity or diversity. Orthogonal frequency division multiplexing (OFDM) is a popular technique for wireless high data-rate transmission because it enables efficient use of the available bandwidth and a simple implementation. It divides the frequency selective fading channel into parallel flat fading subchannels. The combination of MIMO and OFDM is a promising wireless access scheme [1]. Successive interference cancellation (SIC) for third generation (3G) long term evolution (LTE) MIMO-OFDM systems is considered in this paper.

The 3G LTE standard includes a downlink transmitter structure, where the data is divided into two streams which are encoded separately [2]. Separate encoding and modulation allows the use of different modulation methods and code rates on different layers. It also enables the separate decoding of the layers in the receiver. Therefore, a decoded layer can be used in interference cancellation.

Sphere detectors calculate the maximum likelihood (ML) solution by taking into account only the lattice points that are inside a sphere of a given radius [3]. This reduces the computational complexity compared to the ML algorithm. List sphere detectors (LSD) approximate the maximum *a posteriori* probability (MAP) detector and provide soft outputs for the decoder [4]. The K-best LSD algorithm is a modification of the K-best algorithm [5].

Instead of jointly detecting signals from all the antennas, the strongest signal can be detected first and its interference can be cancelled from each received signal [6]. In channel coded systems, the detected symbols are decoded before cancellation. Because horizontal encoding is used, each layer can be decoded and cancelled separately. The soft bit decisions from the turbo decoder are used to calculate symbol expectations. The expectations are cancelled from the remaining layers.

In this paper, the complexity performance tradeoff between the K-best LSD receiver and an MMSE based SIC receiver is presented. Their performances are compared to those of LMMSE, MAP and ML detectors. The MAP detector is a LSD with a full list size. The ML detector is a depth-first LSD with a list size 1. The latencies of the K-best LSD and the SIC receiver are compared and their suitability for a 3G LTE MIMO-OFDM system is considered. The receivers are designed for a 2×2 antenna system and QPSK, 16-QAM and 64-QAM. The receivers are implemented with Xilinx System Generator and synthesized to a field programmable gate array (FPGA). The word lengths are determined via computer simulations.

The paper is organized as follows. The system model is presented in Section 2. The SIC algorithm is introduced in Section 3. The K-best LSD algorithm is introduced in Section 4. Some performance examples are presented in Section 5. The complexities and latencies are compared in Section 6. Conclusions are presented in Section 7.

2. SYSTEM MODEL

An OFDM based MIMO transmission system with N transmit (TX) and M receive (RX) antennas, where $N \leq M$, is considered in this paper. A layered space-time architecture with horizontal encoding is applied. The system model is illustrated in Figure 1. The data is divided into two streams which are encoded separately. The coded data is interleaved, modulated and mapped to different antennas. In the receiver, the received signal is detected jointly or separately, log-likelihood ratios (LLR) are created from the detected symbols which are then deinterleaved. Decoding is also performed separately.

The received signal can be described with the equation

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

where P is the number of subcarriers, $\mathbf{x}_p \in \mathbb{C}^{N \times 1}$ is the transmitted signal, $\eta_p \in \mathbb{C}^{M \times 1}$ is a vector containing identically distributed complex Gaussian noise with variance σ^2 and $\mathbf{H}_p \in \mathbb{C}^{M \times N}$ is the channel matrix containing complex Gaussian fading coefficients. The entries of $\mathbf{x}_p$ are from a complex QAM constellation Ω and $|\Omega| = 2^Q$, where Q is the

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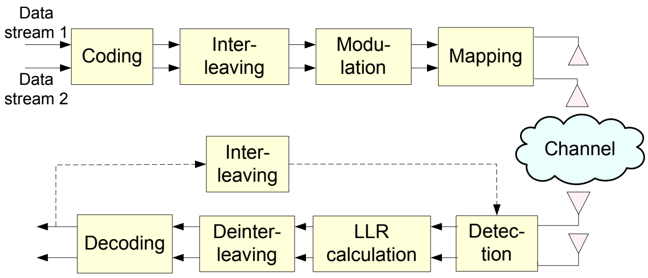

Figure 1: The MIMO-OFDM system model in 3G LTE.

number of bits per symbol. The set of possible transmitted symbol vectors is Ω^N.

3. THE SIC ALGORITHM

Instead of jointly detecting signals from all the antennas, the strongest signal is detected first and its interference is cancelled from each received signal. Then the second strongest signal is detected and cancelled from the remaining signals and so on. The detection method is called successive nulling and interference cancellation [6].

The soft SIC receiver is illustrated in Figure 2. The first layer is detected with a LMMSE detector. The LLR block calculates LLR values from the LMMSE outputs. The deinterleaved stream is decoded with a turbo decoder and symbol expectations are calculated. The expectations are cancelled from the second layer. The first layer remains the same after the second iteration.

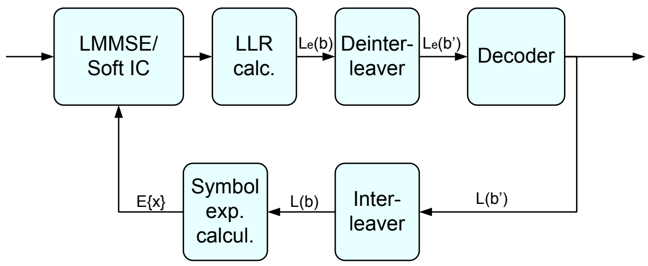

Figure 2: The soft IC receiver.

The weight matrix is calculated with MMSE algorithm

$$\mathbf{W} = (\mathbf{H}^{\mathrm{H}}\mathbf{H} + \sigma^2 \mathbf{I}_M)^{-1}\mathbf{H}^{\mathrm{H}}, \tag{2}$$

where $\mathbf{H}$ is the channel matrix, σ^2 is the noise variance, $(\cdot)^{\mathrm{H}}$ is the complex conjugate transpose and $\mathbf{I}_M$ is a $M \times M$ identity matrix. The layer for detection is chosen according to the post-detection signal-to-noise ratio (SNR) and the corresponding nulling vector is chosen from the weight matrix $\mathbf{W}$ [6]. All the weight matrices in an OFDM symbol are calculated and layer to be detected is chosen according to the average over all the subcarriers.

The LLRs for the decoder are calculated as presented in [7]. The outputs from the LMMSE detector are divided into real and imaginary parts and additions and multiplications are made based on their location on the Gray coded constellation.

The detected layer is decoded and symbol expectations from the soft decoder outputs are calculated as

$$E\{x\} = (\frac{1}{2})^k \sum_{x_l \in \Omega} x_l \prod_{i=1}^{k} (1 + b_{i,l} \tanh(\mathrm{logP}\{c_i\}/2)), \tag{3}$$

where $\mathrm{logP}\{c_i\}$ are the LLRs of coded bits corresponding to x, $b_{i,l}$ are bits corresponding to constellation point x_l, Ω is the symbol alphabet and k is the number of bits per symbol. Here, the calculation is simplified to

$$E\{x\}_{re} = \mathrm{sign}((\mathrm{logP}_i) S \mathrm{abs}(\tanh(\mathrm{logP}_{i+2})). \tag{4}$$

The constellation point S is chosen to be 1,3,5 or 7 depending on the signs of logP_{i+1} and logP_{i+2} in the case of 64-QAM.

4. THE K-BEST LSD ALGORITHM

List sphere detectors can be used to approximate the MAP detector and to provide soft outputs for the decoder [4]. The sphere detector algorithms solve the ML solution with a reduced number of considered candidate symbol vectors. They take into account only the lattice points that are inside a sphere of a given radius. The condition that the lattice point lies inside the sphere can be written as

$$||\mathbf{y} - \mathbf{H}\mathbf{x}||^2 \quad \leq \quad C_0. \tag{5}$$

After QR decomposition (QRD) of the channel matrix $\mathbf{H}$ in (5), it can be rewritten as

$$||\mathbf{y}' - \mathbf{R}\mathbf{x}||^2 \quad \leq \quad C_0^{'}, \tag{6}$$

where $C_0^{'} = C_0 - ||(\mathbf{Q}')^{\mathrm{H}}\mathbf{y}||^2$, $\mathbf{y}' = \mathbf{Q}^{\mathrm{H}}\mathbf{y}$, $\mathbf{R} \in \mathbb{C}^{N \times N}$ is an upper triangular matrix with positive diagonal elements, $\mathbf{Q} \in \mathbb{C}^{M \times N}$ is a matrix with orthogonal columns and $\mathbf{Q}' \in \mathbb{C}^{M \times (M-N)}$ is a matrix with orthogonal columns.

The squared partial Euclidean distance (PED) of $\mathbf{x}_i^N$, i.e., the square of the distance between the partial candidate symbol vector and the partial received vector, can be calculated as

$$d(\mathbf{x}_i^N) = \sum_{j=i}^{N} \left| y_j^{'} - \sum_{l=j}^{N} r_{j,l} x_l \right|^2, \tag{7}$$

where $i = N \ldots, 1$ and $\mathbf{x}_i^N$ denotes the last $N - i + 1$ components of vector $\mathbf{x}$ [3].

The K-best algorithm [5] is a breadth-first search based algorithm, and keeps the K nodes which have the smallest accumulated Euclidean distances at each level. If the PED is greater than the squared sphere radius C_0, the corresponding node will not be expanded. The K-best LSD algorithm was chosen for implementation for its constant throughput and pipelining potential.

A LSD structure is presented in Figure 3. The channel matrix $\mathbf{H}$ is first decomposed to matrices $\mathbf{Q}$ and $\mathbf{R}$ in the QR-decomposition block. Euclidean distances between the receiver signal vector $\mathbf{y}$ and possible transmitted symbol vectors are calculated in the LSD block. The candidate symbol list is demapped to binary form. The log-likelihood ratios are calculated in the LLR block. The LLR $L(x_k)$ for the transmitted bit k can be determined with

$$\begin{aligned} L(x_k) &= \ln \frac{\Pr(x_k = +1|\mathbf{y})}{\Pr(x_k = -1|\mathbf{y})} \\ &= \ln(p(\mathbf{y}|x_k = 1)) - \ln(p(\mathbf{y}|x_k = -1)). \end{aligned} \tag{8}$$

The approximation of $L(x_k)$ in (8) is calculated using a small look-up table and the Jacobian logarithm

$$\text{jacln}(a_1,a_2) := \ln(e^{a_1}+e^{a_2}) = \max(a_1,a_2)+\ln(1+e^{-|a_1-a_2|}). \quad (9)$$

The Jacobian logarithm in (9) can be computed without the logarithm or exponential functions by storing $r(|a_1-a_2|)$ in a look-up table, where $r(\cdot)$ is a refinement of the approximation $\max(a_1,a_2)$. [4] Limiting the range of LLRs reduces the required list size K [8].

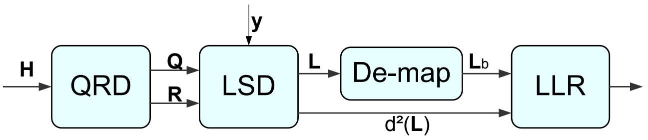

Figure 3: The list sphere detector.

5. PERFORMANCE EXAMPLES

The performance of the SIC detector is compared to that of the K-best LSD, the MAP detector, the LMMSE detector and maximum likelihood (ML) detector. The frame error rates (FER) vs. signal to noise ratio (SNR) per bit in a 2×2 antenna system, 16-QAM modulation, $1/2$ code rate and base station (BS) antenna separation of 4 λ are presented in Figure 4. The results with BS antenna separation of 0.5 λ and therefore in a more correlated channel are presented in Figure 5. The used channel model is Winner urban micro-cell [9] and the bandwidth is 5 MHz with 300 used subcarriers. The simulation length was 1000 frames. The MAP detector has a better performance than the ML detector in a coded system. The LLRs for the decoder are more accurate when calculated from a list of symbol candidates than from a single symbol. It can be seen when comparing the SIC and LMMSE performance that cancelling the interference from one layer improves the performance several dBs. The performance of the SIC receiver is worse than that of the K-best LSD receiver in high correlation channels. However, with low correlation, the SIC receiver outperforms the LSD. Similar performance was observed with all modulation schemes. In a high correlation channel, the cancelled symbols are more often incorrect which causes error propagation and leads to performance degradation.

6. IMPLEMENTATION COMPARISONS

6.1 K-best LSD

The top level architecture of the K-best LSD is presented in Figure 6. The K-best LSD architecture is modified from [10]. A 2×2 antenna system with a real signal model is assumed. The receiver signal vector $\mathbf{y}$ is multiplied with matrix $\mathbf{Q}$ in the matrix multiplication block. Euclidean distances between the last symbol in vector $\mathbf{y}'$ and possible transmitted symbols are calculated in block PED1 with $d(\mathbf{x}_4^2) = ||y_4' - r_{4,4}x_2||^2$. The resulting lists of symbols and Euclidean distances are not sorted at the first stage. The distances are added to Euclidean distances $d(\mathbf{x}_3^2) = ||y_3' - (r_{3,3}x_3 + r_{3,4}x_4)||^2$ calculated in PED2 block. The lists are sorted and K partial symbol vectors with the smallest Euclidean distances are kept. PED3 block calculates $d(\mathbf{x}_2^2) = ||y_2' - (r_{2,2}x_2 + r_{2,3}x_3 + r_{2,4}x_4)||^2$

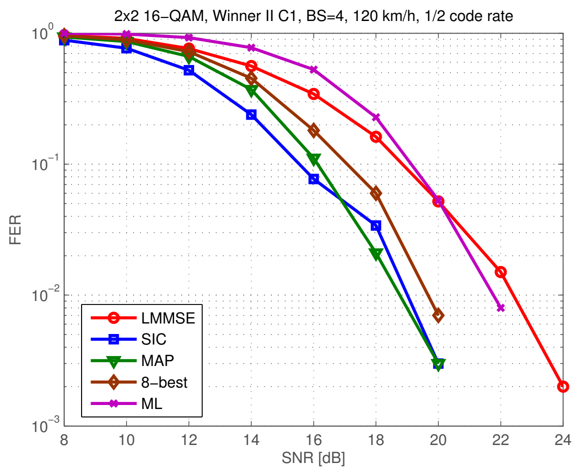

Figure 4: FER vs. SNR with BS antenna separation 4 λ.

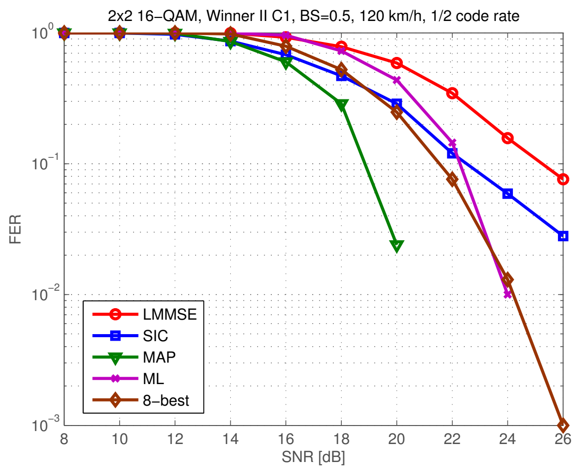

Figure 5: FER vs. SNR with BS antenna separation 0.5 λ.

which are added to the previous distance and sorted. The last PED block calculates the partial Euclidean distances $d(\mathbf{x}_1^2) = ||y_1' - (r_{1,1}x_1 + r_{1,2}x_2 + r_{1,3}x_3 + r_{1,4}x_4)||^2$. After adding the previous distances to $d(\mathbf{x}_1^2)$, the lists are sorted and the final K symbol vectors are demapped to bit vectors and their Euclidean distance used in the LLR calculation.

The LLR calculation block is presented in Figure 7. The Euclidean distances $d^2(\mathscr{L})$ are divided by square root of the noise variance σ. Based on each bit on the bit vector corresponding to the current candidate symbol, the distance is saved to a register. The distance is subtracted from the previous result. The refinement term from (9) comes from the look up table. The result from the look up table and the maximum of the distance and previous results are added together and saved to the corresponding register. The final results corresponding to bits 0 and 1 are subtracted. The LLRs are limited between 8 and -8 [8].

The K-best LSD receiver complexity is presented in Table 1. The complexity is presented in FPGA slices, 18-Kbit blocks of random access memory (BRAM) and 18-bit $\times$ 18-bit multipliers. All blocks have been synthesized to a Xilinx Virtex-IIv6000 FPGA. Control logic between the

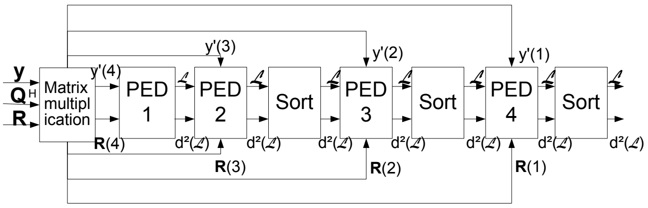

Figure 6: The top level architecture of the K-best LSD.

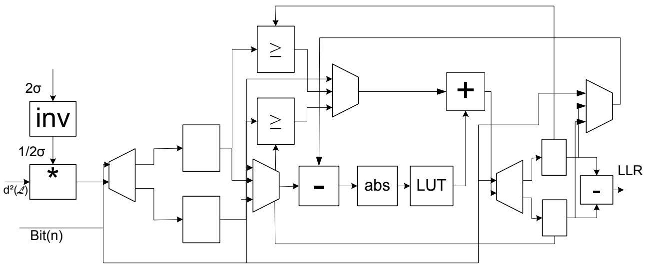

Figure 7: The LLR calculation block.

blocks and registers to store results have not been included in the complexity estimations. The QR-decomposition block is the squared Givens rotation (SQR) based weight calculation block from [11]. The word lengths are mainly 16 bits and computer simulations have been performed to confirm that there is no performance degradation. The sorters are insertion sorters. The maximum list size of 16 was used in the implementation. The sorters have 16 registers in which the smallest Euclidean distance are kept during sorting. The divider is the most complex part of the LLR calculation block.

Table 1: The K-best LSD receiver complexity

Block	Slices	BRAM	Emb. mult.
QRD	7422	14	77
K-best LSD	7147	46	30
Demapping	48	1	
LLR calculation	1045		1
Total	15662	61	108
Available	33792	144	144

6.2 Soft interference cancellation

The SIC receiver consists of a LMMSE detector, a LLR calculation block, a symbol expectation calculation block and an interference cancellation block as presented in Figure 2. The architecture of the 16-QAM part of LLR calculation is presented in Figure 8.

The 16-QAM part of the symbol expectation calculation architecture is presented in Figure 9. The expectations are calculated from the soft values from the decoder. Absolute values of the first two LLRs are calculated and a look up table is used to get an approximate hyperbolic tangent value. The tangent value is multiplied with 3 if the LLR is larger than 0. The results are then multiplied with the signs of the last two LLRs.

The complexity of the SIC receiver is presented in Table 2. The LMMSE complexity comes from the SGR based

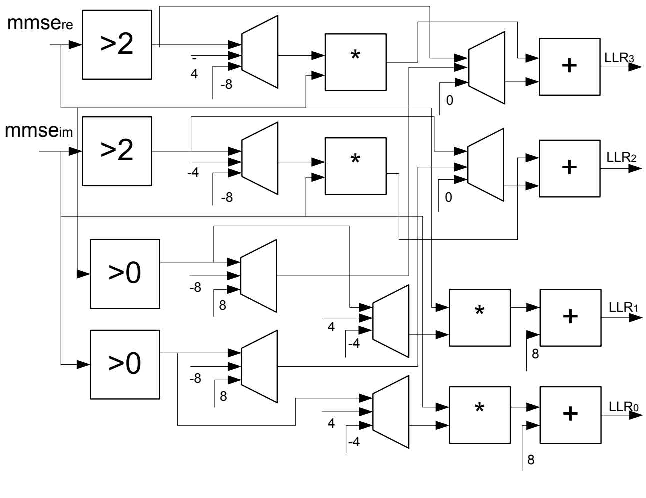

Figure 8: LLR calculation.

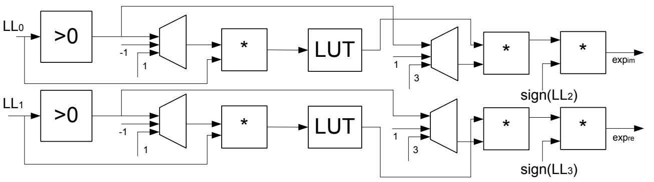

Figure 9: Symbol expectation calculation.

LMMSE detector in [11]. The interleaver is basically a shift register with 600 7 bit registers. The SIC detector includes registers to store the weight and input matrices. The word lengths were determined with computer simulations. In symbol expectation and LLR calculation blocks, the word lengths are mainly 16 bits.

Table 2: The SIC receiver complexity

Block	Slices	BRAM	Emb. mults.
LMMSE (SGR)	11346	28	89
LLR calculation	213	2	13
Interleaver	3500		
Symbol. exp. calculation	204	5	4
SIC	1982		8
Total	17245	35	114
Available	33792	144	144

6.3 Latency comparison

Latency estimations of the real valued K-best LSD and the SIC receiver are presented in Tables 3 and 4. The latencies are in sample periods and they are expressed in total latency of the block and the sample periods in which each subcarrier is processed after the initial latency. The K-best LSD block has the highest latency in the LSD receiver. A new subcarrier can be processed every 9 sample periods with QPSK, every 33 sample periods with 16-QAM and every 129 sample periods with 64-QAM. The LLR calculation duration depends on the LSD list size. The list size is assumed to be 4 with QPSK, 8 with 16-QAM and 16 with 64-QAM.

All the weight matrices in an OFDM symbol have to be calculated before a decision is made on which layer to detect

Table 3: Latency of the K-best LSD receiver

Block	K-best LSD
QRD	150 + 4
K-best LSD (QPSK)	66 + 9
K-best LSD (16-QAM)	172 + 33
K-best LSD (64-QAM)	600 + 129
Demap and LLR (QPSK)	12 + 8
Demap and LLR (16-QAM)	36 + 32
Demap and LLR (64-QAM)	68 + 64
Total (QPSK)	3869 (300 sc)
Total (16-QAM)	12121 (300 sc)
Total (64-QAM)	42317 (300 sc)

first. The weight matrices are calculated when the channel realization changes, i.e., once in 7 OFDM symbols. An approximate LLR calculation from the LMMSE outputs is used instead of Euclidean distance calculations to decrease the latency of the SIC receiver [7]. This causes only minor performance degradation compared to Euclidean distance calculations.

The symbol expectation calculation has the highest latency in the SIC receiver but since the outputs are symbols, it does not have a too great impact on the overall latency. There are always 300 symbols calculated in the symbol expectation block. The number of output bit LLRs from the LLR calculation depends on the modulation.

Table 4: Latency of the SIC receiver

Block	SIC
LMMSE	150 + 4
LLR calc. (QPSK)	2 + 1
LLR calc. (16-QAM)	3 + 1
LLR calc. (64-QAM)	5 + 1
Symbol exp. calculation (QPSK)	8 + 2
Symbol exp. calculation (16-QAM)	14 + 4
Symbol exp. calculation (64-QAM)	17 + 6
SIC	7 + 1
Total (QPSK)	2402 (300 sc)
Total (16-QAM)	4558 (300 sc)
Total (64-QAM)	6711 (300 sc)

The latency of turbo decoding is included in the total latency estimations. The latency of a turbo decoder with a parallel architecture is calculated from the results given in [12]. The total latencies are for processing 300 subcarriers. Pipelining is included in the total latency calculations. The turbo decoder limits pipelining in the SIC receiver in a way that all the subcarriers have to be decoded before moving to the symbol expectation calculation.

In the 3G LTE specifications, a 0.5 ms slot has been allocated for 7 or 6 (depending on cyclic prefix length) OFDM symbols [2]. This leaves a maximum of 83 μs to process 300 subcarriers. With a 70 MHz clock rate, the SIC receiver would meet the timing requirements with QPSK and 16-QAM and achieve roughly a 35 Mbps throughput of coded bits. The K-best LSD would meet the requirements only with QPSK.

7. CONCLUSIONS

The performance, complexity and latency of the K-best LSD and the SIC receivers was compared. The receivers were designed for a 2×2 antenna system and for QPSK, 16-QAM and 64-QAM. The performance of the soft interference cancellation receiver depends more on the channel conditions than that of the K-best LSD. The SIC receiver performs worse than the K-best LSD in channels with highly correlated streams but with low correlations the SIC receiver performs better. The complexity of the SIC receiver is slightly higher than that of the K-best LSD receiver but the latency is higher with the K-best LSD. The timing bottleneck in the K-best LSD receiver is the LSD block. The SIC receiver would meet the timing requirements in the 3G LTE system with QPSK and 16-QAM with the used implementation methods and technology.

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