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**Tobias Seifert**

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Frequency-Selective MIMO Channels:  
Algorithms and Implementations**

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Technische Universität Dresden

**Turbo Receivers for Equalizing  
Frequency-Selective MIMO Channels:  
Algorithms and Implementations**

**Tobias Seifert**

von der Fakultät Elektrotechnik und Informationstechnik  
der Technischen Universität Dresden

zur Erlangung des akademischen Grades

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# Abstract

Received signals of modern wireless communications systems are impaired by temporal and spatial interferences between the symbols. Consequently, a sophisticated equalizer is required as an essential component of the receiver. When *a priori* knowledge based on decoder results is taken into account in the equalization procedure, interference can be reduced more efficiently than in conventional low-complex receivers. These schemes are referred to as *turbo equalization*.

This work focuses on turbo receiver schemes to equalize frequency-selective MIMO channels, which introduces intersymbol interference (ISI) and inter-antenna interference (IAI). The thesis is divided into two parts: The first part (Chapter 4) investigates different MMSE-based algorithms in terms of communications performance and computational complexity. In this context, a novel multi-iterative turbo receiver is proposed to enable interference-aware receiving with respect to the given channel scenario. It is furthermore shown, that normalizing the filter coefficients reduces the equalization bias and improves significantly the reliability of the transmission. The second part (Chapter 5) demonstrates an implementation of the developed algorithm based on a programmable solution. The equalizer application has been profiled whereas matrix inversion was identified as the most computational intensive operation. Starting from a RISC processor instruction set architecture, new equalizer-specific functional units (FUs) have been developed and integrated in order to accelerate both non-recursive and recursive operations. The design was optimized towards high area-efficiency, thus increasing the performance throughput with reasonable low additional hardware effort. In contrast to ASIC implementations, the resulting ASIP core enables very high flexibility to support different equalizer modes along with moderate to high performance.



# Kurzfassung

Wichtiger Bestandteil gegenwärtiger und zukünftiger Mobilfunksysteme ist die Verwendung mehrerer Sende- und Empfangsantennen, die auf Empfangsseite zu räumlicher Überlagerung der Sendesignale führen. In Verbindung mit Mehrwegeausbreitung sind diese Signale zusätzlich von sogenannter zeitlicher Intersymbol-Interferenz geprägt. Zur Auflösung der Interferenzen benötigt es einen Entzerrer als zentrale Verarbeitungskomponente. Die vorliegende Arbeit beschäftigt sich mit iterativen Empfängerstrukturen, auch Turbo-Empfänger genannt, die einen signifikanten Leistungsgewinn der Übertragungszuverlässigkeit ermöglichen. Dabei werden neuartige, mehrfach-iterative Konzepte vorgestellt und sowohl hinsichtlich ihrer algorithmischen Komplexität als auch ihrer Leistungsfähigkeit untersucht. Neben algorithmischen Betrachtungen stehen insbesondere effiziente Implementierungen auf Basis einer erweiterten Befehlssatzarchitektur zur Beschleunigung der Kernoperationen des Entzerrers im Fokus dieser Arbeit.



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Dresden, May 2017

Tobias Seifert



# Contents

<b>Notation and Symbols</b>	<b>xxv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Scope and Outline . . . . .	2
1.2 Notation . . . . .	4
<b>2 Fundamentals</b>	<b>7</b>
2.1 Multipath Propagation in Wireless Channels . . . . .	7
2.1.1 Input/output model of the wireless channel . . . . .	9
2.2 Modulation Schemes in 4G/5G . . . . .	11
2.2.1 Single-Carrier FDMA in LTE . . . . .	12
2.2.2 Generalized Frequency-Division Multiplexing . . . . .	15
2.3 Channel Scenarios for SC-FDMA Transmission . . . . .	17
2.4 Summary . . . . .	20
<b>3 Channel Equalization and MIMO Detection in non-Iterative Receivers</b>	<b>21</b>
3.1 Communications System Model - Uplink . . . . .	21
3.2 An Overview of Channel Equalization Methods . . . . .	24
3.2.1 Detection based on Maximum Likelihood and Maximum A Posteriori Probability . . . . .	25
3.2.2 Linear Equalization . . . . .	27
3.2.3 Interference Cancellation . . . . .	29
3.2.4 Performance Comparison for Uncoded Data Transmission	30
3.3 Introduction to Turbo Equalization . . . . .	31
3.4 Summary and Conclusions . . . . .	34
<b>4 Applying Turbo Equalization to MIMO Systems</b>	<b>37</b>
4.1 Single-Stage Scheme: Joint Frequency-Domain Turbo Equalizer	38
4.1.1 The Feedforward Path: SISO FDE . . . . .	38
4.1.2 The Feedback Path: Soft Modulation and DFT . . . . .	41
4.1.3 Performance Evaluation of the Single-Stage Scheme . . . . .	43

4.2	Two-Stage Scheme: Frequency-Domain Equalizer plus Time-Domain MIMO Detection . . . . .	45
4.2.1	Extended Equalizer . . . . .	45
4.2.2	Noise Whitener and MIMO Detector . . . . .	48
4.2.3	Aspects of Iterations Scheduling . . . . .	49
4.2.4	Performance Evaluation of the Two-Stage Scheme . . . . .	52
4.3	Boosting the Performance: Filter Normalization . . . . .	61
4.3.1	Biased vs. Unbiased MMSE Equalization . . . . .	61
4.3.2	Bias Reduction for the SISO FDE . . . . .	64
4.3.3	Performance Comparison in Low- and High-ISI Channels . . . . .	65
4.4	Complexity Aspects of the SISO FDE . . . . .	67
4.4.1	Complexity Reduction by Splitting PIC Step into separate IAI and ISI Cancellation Steps . . . . .	67
4.4.2	Complexity Reduction by Introducing a Stop Criterion for Iterations . . . . .	71
4.4.3	Performance-Complexity Analysis with respect to Scalability . . . . .	73
4.5	Summary and Conclusions . . . . .	74
<b>5</b>	<b>Implementing SISO FDE for Application-Specific Instruction-Set Processors</b> . . . . .	<b>77</b>
5.1	Implementation Aspects of the selected SISO FDE Algorithm . . . . .	77
5.1.1	Algorithm Partitioning . . . . .	79
5.1.2	Algorithms for Matrix Inversion . . . . .	84
5.1.3	Fixed-Point Arithmetic . . . . .	89
5.2	Tensilica Xtensa LX5 Processor Architecture . . . . .	90
5.2.1	Processor Model . . . . .	91
5.2.2	Programming Aspects . . . . .	93
5.2.3	Simulation Environment and Development Tool . . . . .	93
5.3	Accelerating SISO FDE by Application-Specific Instruction Set Extensions . . . . .	94
5.3.1	Preliminary Considerations . . . . .	96
5.3.2	Instruction Set Extension: CPLX_DOT_PROD . . . . .	99
5.3.3	Instruction Set Extension: CPLX_FWD_SUBS . . . . .	107
5.3.4	Interleaved Subcarrier Processing . . . . .	112
5.4	Performance Evaluation and Implementation Results . . . . .	114
5.4.1	Speedup-Analysis . . . . .	114
5.4.2	Synthesis Results . . . . .	116
5.4.3	Comparison with Other Research . . . . .	122

5.5	The Tomahawk4 Chip: An SDR MPSoC with Dedicated Turbo Receiving . . . . .	125
5.5.1	Toplevel and Baseband Processing Module Description	126
5.5.2	Energy-Efficiency of the LX5_FDE . . . . .	129
5.6	Summary and Conclusions . . . . .	131
<b>6</b>	<b>Conclusions and Outlook</b>	<b>133</b>
<b>A</b>	<b>Power Delay Profiles</b>	<b>137</b>
<b>B</b>	<b>Derivation of the Equalization Filters</b>	<b>139</b>
B.1	Linear MMSE Detection . . . . .	140
B.2	SISO FDE with arbitrary target channel . . . . .	141
<b>C</b>	<b>Details on Reduced Iteration Complexity based on CRC</b>	<b>145</b>
<b>D</b>	<b>Details on Matrix Inversion and Fixed-Point Implementation</b>	<b>147</b>
D.1	QR Decomposition using Gram-Schmidt orthogonalization . .	147
D.2	Realization of Reciprocal Square Root Extraction . . . . .	148
D.3	Further Details on Fixed-Point Arithmetic of the SISO FDE . .	150
<b>E</b>	<b>Parallelism Analysis for the Matrix Multiplication</b>	<b>151</b>
<b>F</b>	<b>Overview of TIE Instruction Set Extensions</b>	<b>153</b>
	<b>Bibliography</b>	<b>157</b>
	<b>Publications and Patents of the Author</b>	<b>169</b>
	<b>Curriculum Vitae</b>	<b>171</b>



# List of Figures

2.1	Multipath propagation over a wireless channel. . . . .	8
2.2	Continuous-time and discrete-time system view of the transmitter, channel, and receiver. . . . .	11
2.3	Illustration of CP insertion. . . . .	12
2.4	Block diagram of the transmitter for OFDM and SC-FDMA scheme. . . . .	13
2.5	Time-frequency grid of single-carrier and multi-carrier modulation schemes. . . . .	16
2.6	Analysis of the overall mean channel tap power. . . . .	18
2.7	Channel tap power analysis of the original $N$ -length and the effective $M$ -length channel with respect to the channel scenarios defined in Tab. 2.2. . . . .	19
3.1	System model of the LTE-A uplink scenario for the generic MIMO case. . . . .	22
3.2	Overview of equalizer types. . . . .	25
3.3	Effective time-domain system model including a linear filter for equalizing the received signal. . . . .	27
3.4	BER performance of different equalizers for BPSK modulated symbols transmitted over a single-antenna frequency-selective channel. . . . .	31
3.5	Generalized turbo receiver with SISO detector/equalizer and SISO decoder to generate LLR values. . . . .	32
4.1	Effective frequency-domain system model including the SISO FDE with a linear filter matrix and a feedback signal vector. . . . .	38
4.2	Turbo receiver of the single-stage scheme for the $t$ -th transmit layer. . . . .	42
4.3	FER performance comparison between of the single-stage SISO FDE for the low-ISI and high-ISI channel scenario. . . . .	44
4.4	Equivalent communications system model by using the introduced target channel. . . . .	46
4.5	Frequency-domain equalizer and time-domain MIMO detector of the two-stage scheme. . . . .	48

4.6	Normalized noise covariance magnitudes, reflecting spatial noise correlation at different receiving steps. . . . .	49
4.7	Simplified block diagram of the multi-iterative receiver which comprises up to three possible feedbacks. . . . .	49
4.8	Tree graph of the possible iteration schedules. Each path from root node to any other node in the tree describes a unique iterations schedule. . . . .	51
4.9	Number of possible schedules in the multi-iterative receiver for a given maximum latency constraint. . . . .	52
4.10	Simplified block diagrams of the receivers for both single-stage (FDE) and two-stage scheme (FDE-TSD). . . . .	54
4.11	Channel impulse responses for two different channel scenarios.	54
4.12	FER performance comparison between single-stage and two-stage schemes for the low-ISI channel scenario. . . . .	56
4.13	FER performance comparison between single-stage and two-stage schemes for the high-ISI channel scenario. . . . .	57
4.14	Node performance gains w.r.t. root node performance vs. the corresponding node latencies. . . . .	59
4.15	Distribution of soft-modulated symbols for a 16-QAM. . . . .	63
4.16	Means of the equalizer output with (black) and without (gray) normalization of 16-QAM symbols. . . . .	65
4.17	FER performance of the normalized single-stage scheme for the low-ISI channel scenario. . . . .	66
4.18	FER performance of the normalized single-stage scheme for the high-ISI channel scenario. . . . .	66
4.19	Equivalent 3-step SISO FDE to equalize the $m$ -th subcarrier of the $t$ -th transmit layer. Functional identical with single-stage (2-step) SISO FDE in Fig. 4.2. . . . .	68
4.20	Complexity analysis of the SISO-FDE for different MIMO systems according to Tab. 4.2. . . . .	71
4.21	Iteration complexity analysis of normalized single-stage scheme SISO FDE. . . . .	72
4.22	Analysis of complexity and SNR performance of the SISO FDE with respect to the MIMO setup and number of equalization-decoding iterations. . . . .	74
5.1	Qualitative classification of the architecture design space [Sch+05].	79
5.2	Signal flow chart of the partitioned SISO FDE algorithm. . . . .	80
5.3	Data dependency graph of the SISO FDE algorithm. . . . .	83

5.4	Performance of the 16-bit fixed-point SISO FDE compared to floating-point. . . . .	89
5.5	Simplified 5-stage ISA pipeline of the Tensilica Xtensa LX5 core. The highlighted blocks are design-defined blocks developed within this work and used to realize application specific ISA (see Section 5.3). . . . .	91
5.6	TIE design methodology: Design flow of the functional description phase in Xtensa Xplorer (see user guide [Tenb]). . . . .	95
5.7	Generalized pipelined execution of a customized operation. . .	96
5.8	Data dependency graph of the SISO FDE algorithm. . . . .	98
5.9	Illustration of the suboperations of the partitioned SISO FDE algorithm . . . . .	99
5.10	Functional unit CPLX_DOT_PROD to calculate the complex-valued dot product. . . . .	101
5.11	TIE instruction CPLX_DOT_PROD implemented as 4-stage pipeline and used together with specific load and store instructions. . .	103
5.12	Zigzag order of computing the elements and corresponding pseudo code. Each code line can be executed in one cycle. . .	104
5.13	Instruction pipeline to efficiently perform operations using the CPLX_DOT_PROD functional unit. . . . .	106
5.14	TIE instruction CPLX_FWD_SUBS implemented as 4-stage pipeline and used together with specific load and store instructions. . .	108
5.15	Instruction pipeline to efficiently perform operations using the CPLX_FWD_SUBS functional unit. . . . .	111
5.16	Illustration of subcarrier processing. . . . .	112
5.17	Average number of cycles required to operate on a single subcarrier using interleaved processing. . . . .	113
5.18	Cycles for equalizing a frequency-domain received vector on the LX5_FDE. . . . .	116
5.19	TIE-related area breakdown of the LX5_FDE. The listed components in the chart correspond to an area of $0.29 \text{ mm}^2$ . . . . .	118
5.20	Throughput and latency of soft-input soft-output (SISO) frequency-domain equalizer (FDE) and soft-output (SO) FDE with respect to the number of interleaved subcarriers $S$ . . . . .	120
5.21	MPSoC block diagram and die photograph of the Tomahawk4. .	126
5.22	Passed/failed table of the SISO FDE benchmark. . . . .	127
5.23	Relative power and energy consumption of the LX5_FDE. . . .	129
5.24	Power consumption of the LX5_FDE multi-core approach for the target throughput of 500 Mbit/s. . . . .	130

- B.1 System model for the linear equalization without consideration of *a priori* information. . . . . 141
- B.2 System model of the FDE with consideration of *a priori* information. . . . . 141
- D.1 FER performance of the fixed-point SISO FDE for different numbers of Newton-Raphson iterations, originally analyzed in [Pla14]. The simulation setup (e.g., the channel scenario) is different to the one usually used in this thesis. . . . . 149
- E.1 Comparison between different parallelization approaches for DOT\_PROD in terms of (pipelined) execution time. . . . . 152

# List of Tables

2.1	OFDM/SC-FDMA parameters as defined by 3rd Generation Partnership Project (3GPP) . . . . .	14
2.2	Two channel scenarios causing rather low or high amount of ISI. Due to localized subcarrier mapping (SCM), only $M < N$ frequency bins (subcarriers) are occupied. . . . .	18
4.1	Two best iterations schedules found among 52 schedule candidates, based on a setup identical to the one used in Section 4.2.4. . . . .	60
4.2	Number of complex-valued multiplications per subcarrier and iteration for the different algorithmic parts of the feedforward path. . . . .	70
5.1	Input and output variables of the frequency-domain SISO FDE to equalize the $m$ -th subcarrier of a $T \times R$ multiple-input multiple-output (MIMO) system. . . . .	80
5.2	Number of real-valued multiplications to determine the feedforward filter of the SISO FDE for a $T \times R$ MIMO system. . . . .	88
5.3	Memory specification for the fixed-point SISO FDE with $4 \times 4$ MIMO. . . . .	92
5.4	Profiling results comparison of different software implementations of a $4 \times 4$ matrix multiplication in C/C++ (see also [Pla14]). Compiler optimization was set to <i>-O1</i> . . . . .	94
5.5	Time and area results of the different matrix multiplication approaches. Values in brackets refer to a filled pipeline. . . . .	101
5.6	Complexity of matrix multiplications expressed by the number of CPLX_DOT_PROD executions. . . . .	102
5.7	Context of state registers for forward/back substitution. . . . .	109
5.8	Context of state registers for Cholesky decomposition. . . . .	110
5.9	Averaged number of cycles required to perform SISO FDE of a single subcarrier on the LX5_FDE with (application-specific instruction-set processor (ASIP)) and without (RISC) TIEs. . . . .	116
5.10	Area results and comparison based on 65 nm low-power CMOS process. . . . .	117

5.11	Number of accumulated cycles when processing $S$ subcarriers as well as corresponding throughput of LX5_FDE at $f_{\max} = 465$ MHz. Furthermore, $4 \times 4$ MIMO ( $T = 4$ ) with 64-QAM ( $\mu = 6$ bit) is assumed. . . . .	119
5.12	Power consumption of the SISO FDE algorithm for power supply $V_{DD} = 1.25$ V and clock frequency $f = 294$ MHz. . . . .	121
5.13	Efficiency metrics of the SISO FDE based on power and throughput results at $f = 294$ MHz, $V_{DD} = 1.25$ V. For LX5 (LX5_FDE) the throughput is $\bar{\tau} = 2.3$ Mbit/s ( $\bar{\tau} = 39.9$ Mbit/s). . . . .	122
5.14	Comparison of minimum mean square error (MMSE)-parallel interference cancellation (PIC)-based MIMO equalizers/detectors designs. . . . .	124
5.15	Comparison between the 65nm logic synthesis results and the 28nm T4 chip measurements. The number in brackets refer to the expected values when scaling down from 65nm to 28nm. . . . .	128
A.1	Two multipath delay profiles representing a low and high delay spread environment, respectively. . . . .	137
C.1	Relative number of receiver runs for different channel scenarios and different number of equalization-decoding iterations #It. . . . .	145
D.1	Fixed-point format of the input, output, and intermediate variables. While $W$ refers to the total bit-width, $I$ refers only to the variable's integer part. . . . .	150
E.1	Time and area results of the different matrix multiplication approaches. Bracket values refer to a filled pipeline. . . . .	151
F.1	Calculation order of Cholesky decomposition. . . . .	153
F.2	Overview of all implemented Tensilica instruction extension (TIE) instructions for controlling the two main functional units as well as accessing local memory. . . . .	154
F.3	Helper TIE instructions for register initialization, configuration of barrel shifters, and fetching of lookup table (LUT) data. . . . .	155

# Abbreviations

<b>3GPP</b>	3rd Generation Partnership Project
<b>4G</b>	4th generation of mobile communication technology
<b>5G</b>	5th generation of mobile communication technology
<b>ADC</b>	analog-to-digital converter
<b>ADPLL</b>	all-digital phase-locked loop
<b>ALU</b>	arithmetic logic unit
<b>APP</b>	<i>a posteriori</i> probability
<b>ASIC</b>	application-specific integrated circuit
<b>ASIP</b>	application-specific instruction-set processor
<b>ATE</b>	area-timing-energy
<b>AWGN</b>	Additive white Gaussian noise
<b>BER</b>	bit error rate
<b>BPSK</b>	binary phase shift keying
<b>CDMA</b>	code-division multiple access
<b>CFO</b>	carrier frequency offset
<b>CGRA</b>	coarse-grained reconfigurable architecture
<b>CMOS</b>	complementary metal-oxide-semiconductor
<b>CoMP</b>	coordinated multi-point
<b>CP</b>	cyclic prefix

<b>CQI</b>	channel quality indicator
<b>CRC</b>	cyclic redundancy check
<b>CSI</b>	channel state information
<b>DFE</b>	decision feedback equalizer
<b>DFT</b>	discrete Fourier transform
<b>DPU</b>	data plane processing unit
<b>DSP</b>	digital signal processor
<b>EPA</b>	extended pedestrian A
<b>ETU</b>	extended typical urban
<b>EVA</b>	extended vehicular A
<b>EXIT</b>	extrinsic information transfer
<b>FB</b>	feedback
<b>FDE</b>	frequency-domain equalizer
<b>FDMA</b>	frequency-division multiple access
<b>FEC</b>	forward error correction
<b>FER</b>	frame error rate
<b>FFT</b>	fast Fourier transform
<b>FLIX</b>	flexible-length instruction extension
<b>FPGA</b>	field-programmable gate array
<b>FU</b>	functional unit
<b>GE</b>	gate equivalents
<b>GFDM</b>	generalized frequency-division multiplexing
<b>GPP</b>	general-purpose processor
<b>i.i.d.</b>	independent and identically distributed
<b>IAI</b>	inter-antenna interference
<b>IC</b>	integrated circuit

<b>IDE</b>	integrated development environment
<b>IDFT</b>	inverse DFT
<b>IEEE</b>	Institute of Electrical and Electronics Engineers
<b>IFFT</b>	inverse FFT
<b>ICI</b>	intercarrier interference
<b>IoT</b>	internet of things
<b>ISA</b>	instruction set architecture
<b>ISI</b>	intersymbol interference
<b>ITU</b>	International Telecommunication Union
<b>LLR</b>	log-likelihood ratio
<b>LTE</b>	Long-Term Evolution
<b>LTE-A</b>	LTE Advanced
<b>LUT</b>	lookup table
<b>LX5</b>	Tensilica Xtensa LX5
<b>MAP</b>	maximum <i>a posteriori</i> probability
<b>MGS</b>	modified Gram-Schmidt
<b>MIMO</b>	multiple-input multiple-output
<b>MLD</b>	maximum likelihood detection
<b>MLSE</b>	maximum likelihood sequence estimation
<b>MMSE</b>	minimum mean square error
<b>MPSoC</b>	multiprocessor system-on-a-chip
<b>NoC</b>	Network-on-Chip
<b>NWF</b>	noise whitening filter
<b>OFDM</b>	orthogonal frequency-division multiplexing
<b>OFDMA</b>	orthogonal frequency-division multiple access
<b>PA</b>	power amplifier

<b>PAPR</b>	peak-to-average-power ratio
<b>PDF</b>	probability density function
<b>PDP</b>	power delay profile
<b>PE</b>	processing element
<b>PIC</b>	parallel interference cancellation
<b>PM</b>	processing module
<b>QAM</b>	quadrature amplitude modulation
<b>RB</b>	resource block
<b>RISC</b>	reduced instruction set computing
<b>rms</b>	root mean square
<b>ROM</b>	read-only memory
<b>RTL</b>	register-transfer level
<b>SC-FDMA</b>	single-carrier frequency-division multiple access
<b>SCM</b>	subcarrier mapping
<b>SD</b>	sphere detector
<b>SDK</b>	software development kit
<b>SDR</b>	software-defined radio
<b>SIC</b>	successive interference cancellation
<b>SIMD</b>	single instruction, multiple data
<b>SIMO</b>	single-input multiple-output
<b>SINR</b>	signal-to-interference-plus-noise ratio
<b>SISO</b>	soft-input soft-output
<b>SLP</b>	Super Low Power
<b>SNR</b>	signal-to-noise ratio
<b>SO</b>	soft-output
<b>STA</b>	synchronous transfer architecture

<b>T4</b>	Tomahawk4
<b>TDMA</b>	time-division multiple access
<b>TIE</b>	Tensilica instruction extension
<b>TSD</b>	tuple-based SD
<b>TSMC</b>	Taiwan Semiconductor Manufacturing Company
<b>VLIW</b>	very large instruction word
<b>WiMAX</b>	Worldwide Interoperability for Microwave Access
<b>WLAN</b>	wireless local area network
<b>ZF</b>	zero forcing



# Notation and Symbols

## Operators and Functions

$\mathbb{C}^{n \times m}$	set of complex numbers with dimensions $n \times m$
$\mathbb{R}^{n \times m}$	set of real numbers with dimensions $n \times m$
$\approx$	approximately equal
$\in$	element of
$\subseteq$	subset
$\sum$	summation of values
$\prod$	product of values
$ \cdot $	absolute value of $(\cdot)$
$\ \cdot\ $	$l^2$ -norm (Euclidean norm)
$(\cdot)^T$	transpose of a matrix
$(\cdot)^H$	conjugate transpose of a matrix (hermitian)
$(\cdot)^{-1}$	inverse of a matrix
$(\cdot)_{(\cdot)_t=0}$	sets $t$ -th entry of a vector to zero
$(\cdot)_{\text{diag}(\cdot)=0}$	sets the diagonal entries of a matrix to zero
$\otimes$	Kronecker product
$\arg \max_{\mathbf{x}}(\cdot)$	argument of the maximum of $(\cdot)$ over the set of points $\mathbf{x}$
$\arg \min_{\mathbf{x}}(\cdot)$	argument of the minimum of $(\cdot)$ over the set of points $\mathbf{x}$
$\mathcal{CN}(0, \sigma_n^2)$	zero-mean complex-valued normal distribution of variance $\sigma_n^2$
$\text{Cov}[\cdot]$	covariance matrix of a vector with random variable
$E[\cdot]$	expected value of a random variable
$L(\cdot)$	log-likelihood ratio values of an estimated symbol $(\cdot)$
$P(\cdot)$	probability of event $(\cdot)$
$\text{Var}[\cdot]$	variance of a random variable
$\text{Im}\{\cdot\}$	imaginary part of $\{\cdot\}$

$\max_x\{\cdot\}$  maximum of  $\{\cdot\}$  over the set of points  $x$   
 $\min_x\{\cdot\}$  minimum of  $\{\cdot\}$  over the set of points  $x$   
 $\text{Re}\{\cdot\}$  real part of  $\{\cdot\}$

## Symbols

$\mathbf{0}_{n \times m}$	zero or null matrix
$\mathbf{1}_T$	all-ones vector of length $T$
$a_i$	channel attenuation of path $i$
$A$	area of an integrated circuit
$\mathbf{A}$	intermediate matrix used for matrix inversion
$B_{\text{coh}}$	coherence bandwidth
$B_s$	signal bandwidth
$\underline{\mathbf{b}}$	time-domain feedback signal vector
$\underline{\mathbf{B}}$	frequency-domain feedback signal vector
$\underline{\mathbf{B}}_{\text{ISI}}$	portion of $\underline{\mathbf{B}}$ related to ISI
$\underline{\mathbf{B}}_{\text{IAI}}$	portion of $\underline{\mathbf{B}}$ related to IAI
$\underline{\mathbf{c}}$	time-domain feedforward filter block matrix
$\underline{\mathbf{C}}$	frequency-domain feedforward filter block matrix
$\mathbf{D}_t$	subcarrier mapping matrix of $t$ -th transmit antenna
$E$	energy dissipated by an integrated circuit
$f$	clock frequency
$\mathbf{F}_N$	$N$ -point Fourier matrix
$\mathbf{G}$	invertible $T \times T$ matrix
$h(t)$	continuous-time impulse response
$h[n]$	discrete-time impulse response
$h_{\text{ch}}(t)$	$h(t)$ of the propagation channel
$\vec{\mathbf{h}}_{r,t}$	vector of channel impulse response between $t$ and $r$
$\underline{\mathbf{h}}'_{r,t}$	time-domain channel matrix between $t$ and $r$
$\underline{\mathbf{h}}_{r,t}$	effective $\underline{\mathbf{h}}'_{r,t}$ , excludes non-occupied subcarriers
$\underline{\mathbf{H}}'_{r,t}$	frequency-domain channel matrix between $t$ and $r$
$\underline{\mathbf{H}}_{r,t}$	effective $\underline{\mathbf{H}}'_{r,t}$ , excludes non-occupied subcarriers
$\mathbf{I}_N$	identity matrix with dimensions $N \times N$
$I$	number of bits representing the integer part
$J$	cost function of the mean square error
$K$	number of subcarrier subsets with $K = M/S$
$l$	iteration level of the (multi-iterative) search tree
$L$	memory length of time-dispersive channel
$\hat{L}_j$	reciprocal values of diagonal elements $L_{j,j}$ in $\mathbf{L}$
$\mathbf{L}$	lower triangular matrix of Cholesky decomposition
$m$	time slot or subcarrier ( $m \in \{1, 2, \dots, M\}$ )
$M$	number of occupied subcarriers
$N$	number of available subcarriers
$\underline{\mathbf{n}}'_r$	time-domain noise vector at $r$ -th receive antenna

$\underline{\mathbf{n}}_r$	effective $\underline{\mathbf{n}}'_r$ , excludes non-occupied subcarriers
$\underline{\mathbf{N}}'_r$	frequency-domain noise vector at $r$ -th receive antenna
$\underline{\mathbf{N}}_r$	effective $\underline{\mathbf{N}}'_r$ , excludes non-occupied subcarriers
$P$	number of pipeline stages per functional unit
$r$	receive layer ( $r \in \{1, 2, \dots, R\}$ )
$R$	number of receiving antennas
$S$	number of grouped subcarriers (subcarrier set) with $S \leq M$
$t$	transmit layer ( $t \in \{1, 2, \dots, T\}$ )
$T$	number of transmitting antennas
$T_d$	delay spread of time-dispersive channel
$T_s$	symbol duration of a signal
$\mathbf{u}$	source signal vector
$\mathbf{v}$	encoded $\mathbf{u}$
$V_{DD}$	power supply voltage
$\underline{\mathbf{w}}$	time-domain NWF matrix
$W$	bit-width for fixed-point format (integer and fractional part)
$x(t)$	transmit signal
$x_t$	constellation symbol sent by $t$ -th transmit antenna
$\hat{x}_t$	(hard) estimation of the symbol sent by $t$ -th transmit antenna
$\tilde{x}_t$	equalized (soft) symbol sent by $t$ -th transmit antenna
$\underline{\mathbf{x}}'_t$	time-domain transmit symbol vector sent by $t$ -th antenna
$\underline{\mathbf{x}}_t$	effective $\underline{\mathbf{x}}'_t$ , excludes non-occupied subcarriers
$\underline{\mathbf{X}}'_t$	frequency-domain transmit symbol vector sent by $t$ -th antenna
$\underline{\mathbf{X}}_t$	effective $\underline{\mathbf{X}}'_t$ , excludes non-occupied subcarriers
$y(t)$	received signal
$\tilde{\underline{\mathbf{Y}}}_t$	IAI reduced frequency-domain received signal vector for $t$ -th transmit antenna
$\underline{\mathbf{y}}'_r$	time-domain received symbol vector at $r$ -th antenna
$\underline{\mathbf{y}}_r$	effective $\underline{\mathbf{y}}'_r$ , excludes non-occupied subcarriers
$\underline{\mathbf{Y}}'_r$	frequency-domain received symbol vector at $r$ -th antenna
$\underline{\mathbf{Y}}_r$	effective $\underline{\mathbf{Y}}'_r$ , excludes non-occupied subcarriers

$\delta(t)$	Dirac delta function
$\eta_i$	relative number of the $i$ -th receiver run (range $[0, 1]$ )
$\mu$	number of bits per constellation symbol ( $2^\mu$ -QAM modulation order)
$\sigma_n^2$	noise variance
$\sigma_x^2$	average transmit power per antenna (equal for all antennas)
$\sigma_{\hat{x},t}^2$	mean variance of the estimated symbols of the $t$ -th antenna
$\tau_i$	propagation delay of path $i$ or latency of node $i$
$\tau_{\max}$	maximum latency constraint
$\bar{\tau}$	(average) equalization throughput
$\rho$	code rate
$\mathbf{\Gamma}_{TM}$	Kronecker product of $\mathbf{I}_T$ and $\mathbf{F}_M$
$\Delta f$	subcarrier spacing
$\mathcal{V}$	set of binary codewords $\underline{\mathbf{v}}$
$\mathcal{X}$	set of constellation symbols $\underline{\mathbf{x}}$



Within less than two decades, mobile communication has changed our everyday life like only few other technical innovations before. While in the beginning, digital cellular networks focused on transmission of voice, mobile devices nowadays are particularly used for multimedia applications and data-intensive communication such as video streaming. Even though approximately half of the traffic is offloaded to WLAN fixed networks, the world's mobile data traffic is expected to increase in general by nearly 8-fold between 2015 and 2020 [Cis16]. By then, 75% of that traffic will be video, which demands for increasing requirements on the performance of modern mobile communication systems. Since spectrum is a highly-limited resource, sophisticated transmissions techniques like multiple-input multiple-output (MIMO) antennas have been introduced in modern wireless communication standards such as IEEE 802.16 (WiMAX), 3GPP LTE or LTE Advanced [Ahm14]. MIMO is a techniques for sending multiple data streams simultaneously over the same radio channel. Ideally, it scales the channel capacity linearly with the number of transmitting antennas. Due to signal coupling at the receiver side, the computation effort for detecting the signal streams has drastically increased.

Besides throughput and transmission reliability, which can be improved by MIMO techniques as well, energy-efficiency has become of utmost importance. This demand is not only driven by cell phone users, but by emerging application trends and markets like internet of things (IoT), where different types of wireless sensor devices are connected to the mobile internet. Especially in the uplink, where data is transmitted from the battery-driven mobile device to the base station, it is important to reduce the transmit signal power. Also the dynamic range of the signal should be small to allow the power amplifier to operate more efficiently and to reduce the overall energy consumption. Regarding this, single-carrier modulation leads to much lower peak-to-average-power ratios than multi-carrier modulation<sup>1</sup>, which is why it was deployed in the 3GPP LTE/LTE-A uplink. However, multipath propagation in combination with single-carrier transmission creates temporal

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<sup>1</sup>Multi-carrier modulation mostly refers to orthogonal frequency-division multiplexing (OFDM), which is a spectrally-efficient method to allocate data on multiple carrier frequencies.

coupling between the symbols at the receiver side. This is also known as intersymbol interference (ISI). The larger the bandwidth<sup>2</sup>, the stronger the coupling, which makes especially wideband transmission very susceptible to ISI. Furthermore, possible future transmission scheme candidates, such as generalized frequency-division multiplexing (GFDM), do no longer guarantee orthogonality between subcarriers. As a consequence, another type of interference, referred to as intercarrier interference (ICI), might be considered in the receiving processing.

To tackle all these kinds of occurring interferences, modern wireless receivers hence require an *equalizer* as essential component. The designs for such equalizers are usually based on dedicated hardware to fulfill high throughput requirements. On the other hand, the variety of existing wireless standards impose high demands on the compatibility and flexibility of modern receivers. Consequently, to support these different standards with common hardware resources, application-specific but still programmable realizations have become more and more attractive.

## 1.1 Scope and Outline

In 1995, Douillard and Berrou proposed an iterative procedure for correcting ISI [Dou+95]. Since this procedure was the direct application of turbo codes to an equalizer, it was then called *turbo equalization*. At the same time, it could be demonstrated [SKJ94; Czy97] that single-carrier modulation provides a performance-complexity trade-off similar to multi-carrier OFDM by making use of linear frequency-domain equalization (FDE). In the following years, FDE has hence become a promising equalization approach also in non-linear iterative schemes [BT05; SAS06]. When MIMO techniques came up, new sophisticated time-domain detection methods like tree-search detection [SB10] were developed to effectively benefit from spatial diversity. However, these concepts, even though combined with iterative detection-decoding, have mostly not taken ISI into account but assumed MIMO-OFDM channels only.

This work tries to overcome the separated views and hence investigate communications systems characterized by encoded data transmission over frequency-selective MIMO channels. The focus of the thesis is on receiver

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<sup>2</sup>In LTE-A, subcarrier aggregation enables up to 100 MHz bandwidth [Ahm14].

schemes that generate very reliable estimation results or provide high communication performance. Regarding this, turbo equalization is considered to be the key technique towards this performance. The question arises about how to apply turbo equalization to MIMO systems that suffer from inter-antenna interference (IAI) and ISI? Furthermore, is it still possible and beneficial to use sophisticated MIMO detection methods at feasible complexity? The work investigates the considered schemes from both an algorithmic and implementation perspective. It hence also covers design issues that arise when aiming for a high-performing *and* programmable solution. The remainder of the thesis is organized as follows:

- ▷ **Chapter 2** provides background information about the phenomenon of classical multipath propagation and how to model the frequency-selective channels. The transmission schemes for 3GPP LTE/LTE Advanced are introduced, especially with focus on single-carrier transmission in the uplink. The chapter concludes with a detailed analysis of the channel impulse responses, taking different power delay profiles and bandwidth assumptions into account.
- ▷ **Chapter 3** introduces the encoded communications system model for a generic MIMO setup. An overview about existing equalization and detection methods for those systems is presented, ranging from linear equalization to optimal maximum *a posteriori* probability (MAP) decoding. The concept of turbo receiving to approximate MAP receivers is also introduced.
- ▷ **Chapter 4** extends turbo equalization to MIMO transmission. The channel equalization is performed jointly in the frequency-domain. Subsequently, a multi-iterative receiver scheme, that comprises two stages to specifically address different types of interference, is proposed. It is further demonstrated that normalization of the equalization filter tremendously enhances the communications performance. The chapter concludes with a detailed performance-complexity investigation for different MIMO setups.
- ▷ **Chapter 5** focuses on the hardware implementation of the selected soft-input soft-output FDE running on an application-specific instruction-set processor (ASIP). For this purpose, the equalization algorithm is firstly prepared for low-cost implementation. The subsequent part develops additional hardware features that can be integrated for accelerating the

execution. Besides synthesis results, measurement results of a silicon implementation of the ASIP are finally presented.

- ▷ **Chapter 6** summarizes the key results of the thesis and gives an outlook about future research topics.

## 1.2 Notation

The following section gives an overview about important notation used within the thesis. An important remark concerns the distinction between frequency-domain and time-domain values, which is essential to improve clarity of formulas. Any further notations can be looked up in the detailed notation list, starting on page xxv.

- Unless otherwise stated, the used variables  $x$  are generally complex-valued, i.e.,  $x \in \mathbb{C}$ .
- Italic characters (e.g.,  $x$ ,  $X$ ) indicate scalar variables or constants. Bold characters (e.g.,  $\mathbf{x}$ ,  $\mathbf{X}$ ) always represent vectors or matrices. Hereby,  $x_i$  identifies the  $i$ -th element of the vector. If  $\mathbf{x}$  is a matrix,  $x_{jk}$  identifies the element placed in the  $j$ -th row and  $k$ -th column.
- Vectors and matrices that refer to an  $M$ -length SC-FDMA symbol are additionally underlined, e.g.,  $\underline{\mathbf{x}}$ . The dimension length of those vectors and matrices is always an integer multiple of  $M$ .
- SC-FDMA related vectors and matrices are represented either in time- or frequency-domain. Lower case vectors or matrices (e.g.,  $\underline{\mathbf{x}}$ ,  $\underline{\mathbf{H}}$ ) indicate time-domain representation. Upper case vectors or matrices (e.g.,  $\underline{\mathbf{X}}$ ,  $\underline{\mathbf{H}}$ ) indicate frequency-domain representation.
- SC-FDMA related vectors are often stacked subvectors. While  $\underline{\mathbf{x}}_j$  addresses the  $j$ -th subvector,  $\mathbf{x}[m]$  composes a vector based on the  $m$ -th elements of all subvectors. To address a scalar in the stacked vector,  $x_j[m]$  is used. Note that the underline has been removed since the latter two examples do not refer to a complete SC-FDMA symbol anymore, but to a single time slot or subcarrier  $m$ .

- SC-FDMA related matrices are often block matrices. To address the submatrix in the  $j$ -th row and  $k$ -th column, the notation the  $\underline{\mathbf{H}}_{j,k}$  is used. To extract a matrix composed of the  $m$ -th diagonal element of all submatrices, the notation  $\mathbf{H}[m]$  is used.
- $\mathbf{H}^H$  and  $\mathbf{H}^T$  denote the hermitian and transpose of a matrix/vector  $\mathbf{H}$ , respectively.  $\mathbf{H}^{-1}$  denotes the inverse of the squared matrix  $\mathbf{H}$ .
- $\mathbf{F}_M$  and  $\mathbf{F}_M^H$  are the Fourier matrix of an  $M$ -point DFT and the inverse Fourier matrix of an  $M$ -point IDFT, respectively.

