Digital Communications
hrsg. von Prof. Dr.-Ing. Peter Adam Höher

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Channel Coding in Molecular Communication

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Preface

The work presented in this dissertation is the outcome of my research conducted at the Chair of Information and Coding Theory at the Christian-Albrechts-Universität zu Kiel.

My special thanks belong to my supervisor Prof. Dr.-Ing. Peter Adam Hoeher, who has always supported, motivated, and inspired me through fruitful discussions. Under his supervision I had the opportunity to research freely and to let ideas come to life. Furthermore, I would like to thank my two co-referees Prof. Dr.-Ing. Robert Schober and Prof. Dr. H. Birkan Yilmaz for their interest in my work, their constructive feedback, and their valuable time.

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Kiel, October 2020 Martin Damrath

Abstract

This dissertation establishes and analyzes a complete molecular transmission system from a communication engineering perspective. Its focus is on diffusion-based molecular communication in an unbounded three-dimensional fluid medium. As a basis for the investigation of transmission algorithms, an equivalent discrete-time channel model (EDTCM) is developed and the characterization of the channel is described by an analytical derivation, a random walk based simulation, a trained artificial neural network (ANN), and a proof of concept testbed setup. The investigated transmission algorithms cover modulation schemes at the transmitter side, as well as channel equalizers and detectors at the receiver side. In addition to the evaluation of state-of-the-art techniques and the introduction of orthogonal frequency-division multiplexing (OFDM), the novel variable concentration shift keying (VCSK) modulation adapted to the diffusion-based transmission channel, the low-complex adaptive threshold detector (ATD) working without explicit channel knowledge, the low-complex soft-output piecewise linear detector (PLD), and the optimal *a posteriori* probability (APP) detector are of particular importance and treated. To improve the error-prone information transmission, block codes, convolutional codes, line codes, spreading codes and spatial codes are investigated. The analysis is carried out under various approaches of normalization and gains or losses compared to the uncoded transmission are highlighted. In addition to state-of-the-art forward error correction (FEC) codes, novel line codes adapted to the error statistics of the diffusion-based channel are proposed. Moreover, the turbo principle is introduced into the field of molecular communication, where extrinsic information is exchanged iteratively between detector and decoder. By means of an extrinsic information transfer (EXIT) chart analysis, the potential of the iterative processing is shown and the communication channel capacity is computed, which represents the theoretical performance limit for the system under investigation. In addition, the construction of an irregular convolutional code (IRCC) using the EXIT chart is presented and its performance capability is demonstrated. For the evaluation of all considered transmission algorithms the bit error rate (BER) performance is chosen. The BER is determined by means of Monte Carlo simulations and for some algorithms by theoretical derivation.

Kurzfassung

In dieser Dissertation wird ein komplettes molekulares Übertragungssystem aus nachrichtentechnischer Sicht geschaffen und analysiert. Der Schwerpunkt liegt dabei auf einer diffusionsbasierten molekularen Kommunikation in einem unendlich ausgedehnten dreidimensionalen fluiden Medium. Als Grundlage zur Untersuchung von Übertragungsalgorithmen wird ein äquivalentes zeitdiskretes Kanalmodell des Systems entwickelt. Zur Charakterisierung des Kanals werden vier Methoden mit unterschiedlichen Ansätzen beschrieben. Diese basieren auf einer analytischen Herleitung, auf Random-Walk-basierten Simulationen, auf einem trainierten neuronalen Netzwerk und auf einem Demonstratoraufbau. Die untersuchten Übertragungsalgorithmen umfassen auf der Sendeseite Modulationsverfahren, während auf der Empfangsseite Kanalentzerrer und Detektoren betrachtet werden. Neben der Evaluation von aus der Literatur gängigen Techniken und der Einführung von *orthogonal frequency-division multiplexing* (OFDM) sind dabei vor allem die neuartige, an den Übertragungskanal angepasste variable Konzentrationsmodulation, der ohne Kanalkenntnis arbeitende aufwandsgünstige adaptive Schrankendetektor, der aufwandsgünstige abschnittsweise linear approximierende Softdetektor, sowie der optimale *a posteriori probability* (APP) Detektor hervorzuheben. Um die Fehlerwahrscheinlichkeit einer Informationsübertragung zu senken werden Blockcodes, Faltungscodes, Leitungscodes, Spreizcodes und räumliche Codierungen untersucht. Die Codierverfahren werden unter verschiedenen Normalisierungsansätzen analysiert. Dabei werden Gewinne und Verluste gegenüber einer uncodierten Übertragung herausgearbeitet. Neben aus der Literatur gängigen vorwärtsfehlerkorrigierenden Kanalcodes werden auch neuartige, an die Fehlerstatistik des diffusionsbasierten Kanals angepasste Leitungscodes vorgestellt. Darüber hinaus wird das Turbo-Prinzip in den Bereich der molekularen Kommunikation eingeführt, bei dem extrinsische Information iterativ zwischen Detektor und Decoder ausgetauscht wird. Mit Hilfe einer *extrinsic information transfer* (EXIT)-Chart-Analyse wird das Potential der iterativen Verarbeitung aufgezeigt und die Kanalkapazität des Kommunikationssystems berechnet, welche die theoretische Leistungsgrenze für das untersuchte System darstellt. Des Weiteren wird das Design eines irregulären Faltungscodes mit Hilfe der EXIT-Chart

vorgestellt und dessen Leistungsfähigkeit demonstriert. Für die Bewertung aller betrachteten Übertragungsalgorithmen wird die Bitfehlerrate herangezogen, die mit Hilfe von Monte-Carlo-Simulationen ermittelt wird. Zusätzlich wird die Bitfehlerrate für ausgewählte Algorithmen theoretisch hergeleitet.

Contents

1 Introduction **1**

1.1 Overview on Molecular Communication 1

1.2 Motivation and Contributions 3

1.3 State-of-the-Art 5

1.4 Author's Contributions 11

1.5 Structure of Dissertation 19

2 Diffusion-Based Channel Modeling **21**

2.1 System Model and Assumptions 21

2.2 Channel Characterization 24

2.2.1 Random Walk Characterization 25

2.2.2 Analytical Characterization 27

2.2.3 Artificial Neural Network Characterization 33

2.3 Equivalent Discrete-Time Channel Model 36

2.3.1 Poisson Binomial EDTCM 37

2.3.2 Binomial Approximated EDTCM 38

2.3.3 Gaussian Approximated EDTCM 38

2.3.4 Poisson Approximated EDTCM 40

2.3.5 Complexity Discussion 40

2.3.6 Approximation Accuracy Analysis 41

2.4 Testbed Verification 43

2.4.1 Experimental Determination of the Channel Impulse Response . . . 48

2.4.2 Experimental Sequence Transmission 49

3 Transmitter and Receiver Algorithms **53**

3.1 Modulation Schemes 53

3.1.1 On-Off Keying 53

3.1.2 Concentration Shift Keying 57

3.1.3 Variable Concentration Shift Keying 60

3.1.4 Pulse-Position Modulation . . . 63
3.1.5 Molecule Shift Keying . . . 65
3.1.6 Molecule Concentration Shift Keying . . . 67
3.1.7 Bit Error Rate Performance . . . 68
3.2 Channel Equalization and Detection . . . 69
3.2.1 Fixed Threshold Detection . . . 69
3.2.2 Adaptive Threshold Detection . . . 71
3.2.3 Piecewise Linear Detection . . . 74
3.2.4 Zero-Forcing Linear Equalization . . . 77
3.2.5 Decision Feedback Equalization . . . 79
3.2.6 Maximum-Likelihood Sequence Estimation . . . 79
3.2.7 Reduced-State Sequence Estimation . . . 83
3.2.8 A Posteriori Probability Detection . . . 84
3.2.9 Bit Error Rate Performance . . . 85
3.3 Orthogonal Frequency-Division Multiplexing . . . 89
3.3.1 Direct Current Biased Optical OFDM . . . 91
3.3.2 Asymmetrically Clipped Optical OFDM . . . 91
3.3.3 Pulse Amplitude Modulation Discrete Multitone Transmission . . . 92
3.3.4 Bit-loading . . . 92
3.3.5 Bit Error Rate Performance . . . 93

4 Channel Coding Algorithms 99
4.1 Block Codes . . . 100
4.1.1 Repetition Code . . . 101
4.1.2 Cyclic Redundancy Check Code . . . 104
4.1.3 Single Parity Check Code . . . 107
4.1.4 Hamming Code . . . 110
4.1.5 Reed-Solomom Code . . . 114
4.1.6 Low-density Parity-check Code . . . 117
4.1.7 Repeat-Accumulate Code . . . 120
4.1.8 ISI-free Code . . . 124
4.2 Convolutional Codes . . . 126
4.3 Line Codes . . . 132
4.3.1 Run-length Limited Code . . . 132
4.3.2 Weak Sequences Preventing Mapping . . . 135

4.3.3 Weak Sequence Preventing Convolutional Code 140
4.4 Spreading Codes 145
4.4.1 Walsh-Hadamard Codes 146
4.4.2 Maximum Length Sequences 147
4.4.3 Binary Complementary Sequences 147
4.4.4 Spreading Codes for Unipolar Channels 148
4.4.5 Rake Receiver 150
4.4.6 Numerical Results 151
4.5 Spatial Codes 154
4.5.1 MIMO Scenario 154
4.5.2 Alamouti-type Code 156
4.5.3 Repetiton MIMO Code 157
4.5.4 Receiver Combining Techniques 158
4.5.5 Detection 159
4.5.6 Numerical Results 160

5 Turbo Principle 167
5.1 Bit-Interleaved Coded Modulation 167
5.2 Extrinsic Information Transfer Chart 169
5.2.1 Bit Error Rate Prediction 170
5.2.2 Communication Channel Capacity 170
5.3 EXIT Chart Aided Code Design 171
5.4 Numerical Results 172
5.4.1 Communication Channel Capacity Analysis 172
5.4.2 EXIT Chart Analysis 175
5.4.3 EXIT Chart Aided Code Design 177
5.4.4 BER Analysis 179

6 Conclusion and Outlook 187
6.1 Conclusion 187
6.2 Outlook 190

Appendix 193

A Notation 193

B Proofs **203**
B.1 Solution of Fick's Second Law 203
B.2 Identity of Second Derivative 204
B.3 Intersection Point of Two Gaussian Distributions 204

C Simulation Parameters **207**
C.1 Figure 2.8 207
C.2 Figure 3.3, 3.5, 3.8, 3.9, 3.10 207
C.3 Figure 3.7 208
C.4 Figure 3.11 208
C.5 Figure 3.13 208
C.6 Figure 3.15, 3.19, 3.20, 3.21, 3.22 209
C.7 Figure 3.25 209
C.8 Figure 3.26, 3.27, 3.28, 3.29 210
C.9 Figure 3.30 210
C.10 Figure 4.1, 4.2, 4.3, 4.4, 4.5, 4.10, 4.11, 4.13, 4.14 211
C.11 Figure 4.7 211
C.12 Figure 4.15 212
C.13 Figure 4.16, 4.17, 4.19, 4.20 212
C.14 Figure 4.22 213
C.15 Figure 4.26, 4.27 213
C.16 Figure 5.3 214
C.17 Figure 5.4 214
C.18 Figure 5.5 215
C.19 Figure 5.6 215
C.20 Figure 5.7 216
C.21 Figure 5.8 216
C.22 Figure 5.9 217

Bibliography **219**