Analysis and Design of Modern Coding Schemes for Unequal Error Protection and Joint Source-Channel Coding

BY HUMBERTO VASCONCELOS BELTRÃO NETO

A thesis submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy
in Electrical Engineering

JACOBS
UNIVERSITY

UNIVERSIDADE
FEDERAL
DE PERNAMBUCO

Dissertation Committee:
Prof. Dr.-Ing. Werner Henkel, Jacobs University Bremen
Prof. Dr. Valdemar Cardoso da Rocha Jr., Universidade Federal de Pernambuco
Prof. Dr. Jon Wallace, Jacobs University Bremen
Prof. Dr. Gerhard Kramer, Technische Universität München
Prof. Dr. Ricardo Campello de Souza, Universidade Federal de Pernambuco

---

Date of Defense: July 16, 2012
School of Engineering and Science - Jacobs University Bremen

Communications and Coding Series

Humberto Vasconcelos Beltrão Neto

Analysis and Design of Modern Coding Schemes for Unequal Error Protection and Joint Source-Channel Coding

Shaker Verlag
Aachen 2012

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Jacobs Univ. Bremen, Diss., 2012

Copyright Shaker Verlag 2012
All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-1327-6
ISSN 1868-0291

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

To Lúcia, Miriam, and Antônio

Acknowledgments

This work is the result of my research in the School of Engineering and Science at Jacobs University Bremen developed in cooperation with the Department of Electronics and Systems at the Federal University of Pernambuco.

First of all, I would like to thank my both advisors Prof. Dr.-Ing. Werner Henkel and Prof. Dr. Valdemar da Rocha Jr. for their supervision and friendship. I am very grateful not only for their orientation, but also for the confidence and academic liberty they gave me. Furthermore, I want to thank Prof. Dr. Jon Wallace, Prof. Dr. Ricardo Campello, and Prof. Dr. Gerhard Kramer for accepting to join the dissertation committee.

I also would like to thank my colleagues Neele von Deetzen, Khaled Hassan, Abdul Wakeel, Fangning Hu, Jalal Etesami, Alexandra Filip, Khodr Saaifan, Oana Graur, and Apirath Limmanee for their company, friendship, interesting discussions, and support.

I do not have enough words to express my gratitude to Patricia Wand and Moritz Lehmann. They were more than my flatmates and German teachers, they were my family. I also have to thank my old and great friend Leandro Rocha, who even not being in Bremen, was a constant and important presence in my life. My stay in Germany would not have been half as enjoyable without them, and I can surely say they are friends for life.

This section would not be complete if I did not mention the people to whom I dedicate this thesis: my mom Lúcia, my dad Antônio, and my grandma Miriam. Even being thousands of miles away, they were a constant presence and source of inspiration. I would not have gone so far without them, who sometimes gave up their dreams so that I could make mine come true. Thank you for everything!

Finally, I would like to thank the National Counsel of Technological and Scientific Development (CNPq), the German Academic Exchange Service (DAAD), and the German Research Foundation (DFG) for the financial support.

I hereby declare that I have written this Ph.D. thesis independently, unless where clearly stated otherwise. I have used only the sources, the data, and the support that I have clearly mentioned. This Ph.D. thesis has not been submitted for conferral of degree elsewhere.

Humberto Vasconcelos Beltrão Neto
Bremen, July 2012

Abstract

In this thesis, we investigate systems based on error-correcting codes for unequal-error-protecting and joint source-channel coding applications. Unequal error protection (UEP) is a desirable characteristic for communication systems where source-coded data with different importance levels is being transmitted, and it is wasteful or even infeasible to provide uniform protection for the whole data stream. In such systems, we can divide the coded stream into classes with different protection requirements. Among the possible ways to achieve UEP, we focus on solutions based on error-correcting codes.

Regarding UEP solutions by means of coding, we first introduce an analysis of a hybrid concatenation of convolutional codes, which typically arises in the context of turbo coding schemes with unequal-error-protecting properties. We show that the analysis of such a system can be reduced to the study of serial concatenated codes, which simplifies the design of such hybrid schemes.

Additionally, we also investigate the application of graph-based codes for systems with UEP requirements. First, we perform a multi-edge-type analysis of unequal-error-protecting low-density parity-check (LDPC) codes. By means of such an analysis, we derive an optimization algorithm, which aims at optimizing the connection profile between the protection classes within a codeword of a given unequal-error-protecting LDPC code. This optimization allows not only to control the differences in the performances of the protection classes by means of a single parameter, but also to design codes with a non-vanishing UEP capability when a moderate to large number of decoding iterations is applied.

As a third contribution to UEP schemes, we introduce a multi-edge-type analysis of unequal-error-protecting Luby transform (UEP LT) codes. We derive the density evolution equations for UEP LT codes, analyze two existing techniques for constructing UEP LT codes, and propose a third scheme, which we named flexible UEP LT approach. We show by means of simulations that our proposed codes have better performances than the existing schemes for high overheads and have advantages for applications where a precoding of data prior to the channel encoding is needed.

In the last part of the thesis, we investigate joint source-channel coding schemes where low-density parity-check codes are applied for both source and channel encoding. The investigation is motivated by the fact that it is widely observed that for communication

systems transmitting in the non-asymptotic regime with limited delay constraints, a separated design of the source and channel encoders is not optimum, and gains in complexity and fidelity may be obtained by a joint design strategy. Furthermore, regardless of the fact that the field of data compression has reached a state of maturity, there are state-of-the-art applications which do not apply data compression, thus failing to take advantage from the source redundancy in the decoding.

Within this framework, we propose an LDPC-based joint source-channel coding scheme and by means of the multi-edge analysis previously developed, we propose an optimization algorithm for such systems. Based on syndrome source encoding, we propose a novel system where the amount of information about the source bits available at the decoder is increased by improving the connection profile between the factor graphs of the source and channel codes that compose the joint system.

Lastly, by means of simulations, we show that the proposed system achieves a significant reduction of the error floor caused by the encoding of messages that correspond to uncorrectable error patterns of the LDPC code used as source encoder in comparison to existent LDPC-based joint source-channel coding systems.

Contents

1 Introduction **1**

2 Basic Concepts **5**
2.1 Communication system 5
2.2 Transmission model 7
2.3 Channel coding 10
2.3.1 Linear block codes 10
2.3.2 Convolutional codes 11
2.4 Low-density parity-check codes 13
2.4.1 Iterative decoding 15
2.4.2 Density evolution 17
2.4.3 Stability condition 19
2.4.4 Multi-edge-type LDPC codes 20
2.5 Luby transform codes 21
2.5.1 LT encoding 21
2.5.2 Iterative decoder 22
2.6 Extrinsic information transfer charts 23

3 Asymptotic Analysis of Hybrid Turbo Codes **27**
3.1 Hybrid turbo codes 27
3.1.1 Iterative decoding of the parallel concatenated codes 29
3.1.2 Iterative decoding of the serially concatenated codes 30
3.1.3 Hybrid turbo code decoding 31
3.2 Global and local EXIT charts 32
3.2.1 Local EXIT charts 32
3.2.2 Global EXIT charts 34
3.3 Relation between local and global EXIT charts 35
3.4 Construction of the local EXIT chart from the transfer characteristic of the inner and outer codes 38

4 Multi-Edge-Type Unequal-Error-Protecting LDPC Codes **43**
4.1 Unequal-error-protecting LDPC codes 43
4.1.1 System model and notation 45

4.2 Multi-edge-type unequal-error-protecting LDPC codes 45
4.2.1 Edge-perspective notation 46
4.2.2 Asymptotic analysis 47
4.2.3 Optimization algorithm 49
4.3 Simulation results 52
4.3.1 Low number of iterations 52
4.3.2 High number of iterations 57
4.4 Detailed mutual information evolution 61

5 Multi-Edge-Type Unequal-Error-Protecting LT Codes 67
5.1 Multi-edge-type unequal-error-protecting LT codes 68
5.1.1 Node-perspective degree distributions 69
5.1.2 Encoding and decoding 71
5.2 Construction algorithms for unequal-error-protecting LT codes 71
5.2.1 Weighted approach 71
5.2.2 Windowed approach 73
5.2.3 Flexible UEP LT codes 75
5.3 Asymptotic analysis of multi-edge-type UEP LT codes 78
5.4 Simulation results 81

6 LDPC-based Joint Source-Channel Coding 83
6.1 Joint source-channel coding 83
6.2 LDPC-based joint source-channel system 86
6.2.1 Encoder 88
6.2.2 Decoder 90
6.3 Multi-edge notation for joint source-channel factor graphs 91
6.4 Asymptotic analysis 92
6.5 Optimization 98
6.6 Simulation results 100

7 Concluding Remarks 105

A List of Mathematical Symbols 109

B List of Acronyms 113

C Extended Abstract in Portuguese 115

Own Publications 135

Bibliography 136