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博　士　学　位　论　文

码率自适应 LDPC 码的研究

Research on Rate-Compatible LDPC Codes

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摘 要

低密度奇偶校验（low-density parity-check code，LDPC）码具有逼近 Shannon 限的性能、较低的误码平台（error floor）和线性的译码复杂度，在现代信道纠错编码领域中备受关注。随着现代通信服务从单一的低速话音业务迈向各种高速多媒体业务，传输速率与传输条件多样性日益增长，使得通信系统的信道编码技术不仅要具备纠错功能，而且还必须能够根据传输速率和传输条件的变化而自适应地改变码率。面对这一新需求，研究码率自适应 LDPC（rate-compatible LDPC，RC-LDPC）码，使其在延续 LDPC 码各项优势的同时，码率能够自适应地灵活调整，对于进一步推动 LDPC 码的应用化进程具有重要的意义和价值。

本文以近年来 RC-LDPC 码的发展趋势为导向，针对一般 LDPC 码以及几种常见的结构型 LDPC 码，提出了码率自适应实现算法，同时研究了信源信道联合编码系统中的码率自适应问题。主要工作和研究成果如下：

1、研究了有限码长情况下的码率自适应删余型 LDPC 码，分析了当前一种较为通用的删余算法——分组-拣选（grouping and sorting）算法的局限性，证明该算法存在删余码率的上限，即无法实现较高码率的自适应功能；提出改进的分组-拣选算法，在保证性能的前提下，解决了删余码率的瓶颈问题。本文进一步发现并论证了校验节点所连接的删余变量节点个数是影响码型性能的关键因素之一，在此基础上提出了双准则拣选算法，仿真结果显示该算法的性能好于前两种算法。本文所提出的这后两种删余算法均适用于任意 LDPC 码，且删余码率能够无限接近 1。

2、鉴于各种反馈重传系统对高码率性能的首要需求，本文根据不规则重复积累（irregular repeat-accumulate，IRA）码的结构特点，首先揭示了删余和分裂这两种方法的互逆关系，进而提出分裂删余联合算法。不同于传统的、单方向设计思路（直接由母码向高码率或者是低码率设计），本文提出的算法是从性能优秀的高码率母码开始，先分裂母码得到低码率代理码，再通过删余代理码实现码率从低到高的自适应。这样一个新的设计思路结合了分裂和删余这两种方法的长处，既能够像分裂方法一样保证高码率的性能，又兼具删余方法低实现成本的优点。仿真结果显示，分裂删余联合算法所设计出的码率自适应 IRA 码不仅在高

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码率上好于现有各种码率自适应 IRA 码，而且在其他码率上也有明显的性能优势。

3、考虑到大部分码率自适应方法都需要用到高码率码型作为母码，而两边类型 LDPC（two-edge type LDPC，TET-LDPC）码在高码率情况下的性能远好于传统 LDPC 码。本文首先推导了 TET-LDPC 码的外信息转移（extrinsic information transfer，EXIT）函数，并借助 EXIT 方法优化该码型的门限值，进而针对 TET-LDPC 码中导致误码平台的陷阱集（trapping set），提出两个构造准则以降低该码型的误码平台。仿真结果表明，所设计的 TET-LDPC 码好于传统 TET-LDPC 码。

4、为了研究多边类型 LDPC（multi-edge type LDPC，MET-LDPC）码在较广范围内的码率自适应问题，本文选取一类中等码率（0.5）、性能优秀的 MET-LDPC 码作为母码，根据其结构特点，提出了分级删余算法和分级-分组扩展算法，以分别实现码率从 0.5~0.8 以及 0.5~0.2 的自适应功能。其中分级删余算法借鉴并简化了研究成果 1 中的双准则拣选算法，而分级-分组扩展算法与传统扩展算法的区别在于不是从校验矩阵的角度而是从 Tanner 图的角度进行扩展，能够更直接地提高性能。

5、分析了一类信源信道联合编码系统——双 LDPC 码系统，发现该系统对信源熵十分敏感，当信源熵增加时，性能会急剧恶化，此时提高信源码率可以明显改善这一状况。本文首先利用 EXIT 方法估计出该系统的信源码率门限值和信源熵门限值，进而引入码率自适应缩短型 LDPC 码，设计了具有码率自适应功能的双 LDPC 码系统。仿真结果显示，对于不同的信源熵，本文所提出的码率自适应双 LDPC 码系统的误码平台比传统双 LDPC 码系统低了 3~4 个数量级，使得整个信源信道联合编码系统在不同信源熵情况下保持基本一致的性能，增强了系统的鲁棒性。

关键词：LDPC 码，码率自适应，不规则重复积累码，多边类型 LDPC 码，信源信道联合编码

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ABSTRACT

Low-density parity-check (LDPC) codes have attracted significant attention in the area of modern error correcting codes (ECC) due to their capacity-approaching performance, low error floors and linear-time complexity of encoding. Along with the development of modern communication service from low-rate voice transmission to high-rate multimedia application, the variety of transmission rate under different conditions requires ECC to be able to adapt their code rates according to system requirements more than just to correct errors. The research of rate-compatible LDPC (RC-LDPC) codes with good performance and flexible rate adaptability would benefit the application of LDPC codes in future communication systems.

In this thesis, based on general LDPC codes and two structured LDPC codes, several algorithms and strategies are proposed to accomplish rate compatibility and a new application of RC-LDPC codes in a joint source and channel coding system is investigated. The main work and constructions of this thesis are summarized as follows:

1. The design of finite-length rate-compatible punctured LDPC (RCP-LDPC) codes is considered. A widely-used algorithm, grouping and sorting (GS) algorithm is analyzed and the upper bound of the highest rate it can achieve is proved. In order to solve this rate limitation, an improved GS (IGS) algorithm is proposed without any performance degradation. Then we find and prove that the number of punctured variable nodes neighboring check nodes can affect the performance of RCP-LDPC codes. Based on this claim, a new algorithm is proposed which shows better performance than both the GS algorithm and the IGS algorithm in simulation. The two proposed algorithms can be applied to an arbitrary LDPC code to obtain a code rate unlimitedly close to 1.

2. In a hybrid automatic repeat request (HARQ) system with incremental retransmission, one expects the initial transmission(s) of the high-rate code(s) to be powerful. Exploiting the reciprocal relation between splitting and puncturing for irregular repeat accumulate (IRA) codes, a new joint splitting and puncturing method is developed to construct finite-length rate-compatible IRA codes. The proposed method exercises a philosophy different from the conventional “low-rate-up straight” or “high-rate-down straight” approaches, and achieves rate compatibility in three steps: design a good highest-rate code, split it all the way to the lowest rate, and progressively reverse the splitting operation to construct the entire family of rate-compatible codes by puncturing. The joint splitting and puncturing method can ensure the superiority at the highest rate for RC-IRA codes and at the same time benefit from low implement complexity. Simulation shows that compared with the best RC-IRA codes reported so far, the resultant codes not only guarantee superb performance at the highest rate, but also promise very good performance across the board.

3. Since most rate-compatible strategies need high-rate codes as mother codes,

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two-edge type LDPC (TET-LDPC) codes which have better performance than conventional LDPC codes at high rates are apparently good candidates. With the aim to design TET-LDPC codes, the extrinsic information transfer (EXIT) functions are derived first and then used to optimize the thresholds which determine the performance of TET-LDPC codes in the waterfall region. In addition, two construction criteria dealing with the trapping sets of TET-LDPC are given to lower the error floors of TET-LDPC codes. Simulation results show that the designed TET-LDPC codes outperform conventional TET-LDPC codes.

4. The construction of rate-compatible multi-edge type LDPC (MET-LDPC) codes across a wide range of rates is investigated. A class of MET-LDPC codes with moderate rate (0.5) and good performance is considered as the mother code. A puncturing algorithm and an expending algorithm are proposed to accomplish rate-compatibility from 0.5~0.8 and 0.5~0.2 respectively. The first algorithm named level-wise puncturing algorithm arises from the best-performing one in “contribution 1” but much simpler. The second algorithm called grading and grouping algorithm exercises expending based on the Tanner graph rather than the parity-check matrix as conventional methods did.

5. A new class of joint source and channel coding systems named a double LDPC (DLDPC) code system has been developed recently, which consists of a source LDPC code and a channel LDPC code. It is found that the performance of a DLDPC code system deteriorates sharply when the source entropy increases and this problem can be solved by raising the rate of the source LDPC code. Hence a rate-compatible double LDPC (RC-DLDPC) code system is proposed which can adapt its source code rate according to the source entropy. The RC-DLDPC system uses rate-compatible shortened LDPC codes as the source LDPC code whose range of rates can be determined by the source rate threshold and the entropy threshold. We use EXIT charts to estimate these two thresholds. Simulation results show that the proposed RC-DLDPC code system pushes the error floor 3~4 magnitudes lower than the conventional DLDPC code system and enable the system of good performance and high robustness.

Keywords: Low-density parity-check (LDPC) codes, rate-compatible, irregular repeat accumulate (IRA) codes, multi-edge type LDPC (MET-LDPC) codes, joint source-channel coding.

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缩略词表

ACM	adaptive coding and modulation	自适应编码调制
BEC	binary erasure channel	二进制删除信道
BER	bit error rate	误比特率
BP	belief propagation	信度传播
CN	check node	校验节点
CSI	channel state information	信道状态信息
DLDPC	double LDPC	双 LDPC
EXIT	extrinsic information transfer	外信息转移
GS	grouping and sorting	分组拣选
HARQ	hybrid automatic repeat request	混合自动反馈重传机制
IGS	improved GS	改进的 GS
IN	information node	信息节点
IRA	irregular RA	不规则重复积累
IR-HARQ	incremental redundancy HARQ	递增冗余型 HARQ
k-SR	k-step recoverable	k 步可恢复
LDPC	low-density parity-check	低密度奇偶校验
LLR	log likelihood ratio	对数似然比
MET-LDPC	multi-edge type LDPC	多边类型 LDPC
OSI	open system interconnect	开放式系统互连
PN	parity node	奇偶节点
PVN	punctured variable node	删余变量节点
QC-LDPC	quasi-cyclic LDPC	准循环 LDPC
QoS	quality of service	服务质量
RA	repeat-accumulate	重复积累
RC-DLDPC	rate-compatible DLDPC	码率自适应双 LDPC 码
RCE-LDPC	rate-compatible extended LDPC	码率自适应扩展型 LDPC
RC-IRA	rate-compatible IRA	码率自适应 IRA
RC-LDPC	rate-compatible LDPC	码率自适应 LDPC
RCP-IRA	rate-compatible punctured IRA	码率自适应删余型 IRA 码
RCP-LDPC	rate-compatible punctured LDPC	码率自适应删余型 LDPC
RCS-LDPC	rate-compatible shortened LDPC	码率自适应缩短型 LDPC
SNR	signal noise ratio	信噪比
TET-LDPC	two-edge type LDPC	两边类型 LDPC
UEP	unequal error protection	不等差错保护
UPVN	unpunctured variable node	未删余变量节点

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