# 博士学位論文審査要旨

２０１６年2月１７日

論文題目：Spatial Coupling of Serially-Concatenated Codes
（直列連接符号の空間結合に関する研究）
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要 旨：

本論文は、直列連接符号の空間結合に関する研究成果である。直列連接符号は、二つの要素符号を連接して、１つ目の要素符号の出力のビット列が、並び替えてから２つ目の要素符号に入力するように構成される。空間結合は、いくつかのベースとなる符号を結合して新たな符号を構成する手法である。

本研究では、直列連接符号を結合する空間結合直列連接符号を２種類提案する。第２章で符号理論の基礎を解説する。第３章で１つ目の提案符号について述べる。提案符号は、要素符号の１つを畳込み符号としての直列連接符号の空間結合符号で、ガウス通信路において、理論解析で得られた復号性能が、通信路符号化定理が示す理論上の伝送限界に漸近することを示す。さらに実用可能な短い符号長でもそれらの伝送限界に近づくことを確認する。第４章では、第３章で提案された符号を多重接続通信路に適用する。提案符号が、理論解析で得られた復号性能がすべての許容送信電力領域で理論上の伝送限界に漸近するユニバーサル性を示す。

第５章で、２つ目の提案符号の構成法について述べる。この提案符号は、RA（Repeat-Accumulate）符号を要素符号の１つに使用し空間結合された符号である。リピータの回数と累積ビット数の送信割合を調節することで、符号化率が可変である。各符号化率において、理論解析で得られた復号性能がそれぞれの理論上の伝送限界に漸近することを示す。

本研究で提案した直列連接符号の空間結合で得られる符号は、理論上の伝送限界に漸近する高信頼通信を可能にする。さらに、この符号の構成符号の一つは、符号長が短いという特徴を有するので、通信システムへの応用が期待される。

よって、本論文は、博士（工学）（同志社大学）の学位論文として十分な価値を有するものと認められる。

# 総合試験結果の要旨

２０１６年2月１７日

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（直列連接符号の空間結合に関する研究）
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要　　　旨 :

本論文提出者は、工学研究科情報工学専攻博士後期課程に在籍している。本論文の主たる内容は、IEEE Communications Letters, vol. 20, no. 1 および Proceedings of the 8th International Symposium on Turbo Codes & Iterative Information Processing に掲載され、十分な評価を得ている。

2016 年 1 月 23 日 10 時より約 1 時間 50 分にわたって提出論文に関する学術講演会（博士論文公聴会）が開催され、種々の質疑討論が行われたが、論文提出者の説明により十分な理解が得られた。

さらに、講演会終了後、審査委員により論文に関連した諸問題につき口頭試問を実施した結果、十分な学力を有することが確認できた。

提出者は、英語による論文発表および口頭発表を行っており、十分な語学能力を有すると認められる。

よって、総合試験の結果は合格であると認める。

# 博 士 学 位 論 文 要 旨

論 文 題 目：　Spatial Coupling of Serially-Concatenated Codes
（直列連接符号の空間結合に関する研究）

氏　　　名：　Wei Hou　（侯　偉）

要　　　旨：

Spatial coupling is a new technique to structure codes by associating multiple identical base codes. It is worth mentioning that the select of base codes is flexible. Various base codes may derive capacity-approaching coupled codes whose error correction performance are close to theoretical limit shown by channel coding theorem. Since serially-concatenated codes consist of two component codes, we tend to use them as base codes to structure more flexible spatially coupled codes by selecting component codes for some practical features, such as simple encoding, effective decoding and rate adjustability.

In this dissertation, we introduce two kinds of our proposed codes. The first is spatially coupled repeater-combiner-convolutional (SC-RCC) codes. Their base codes consist of repetition code concatenated with convolutional code. The SC-RCC codes have simple encoder construction and effective decoding, since their base codes are easy to encode and their convolutional component codes provide powerful error-correcting ability. Numerical results of analysis and simulation show that SC-RCC codes have decoding performance nearer to theoretical limit than conventional spatially coupled codes in point-to-point communication systems and multiple access channels (MAC). The second kind of proposed codes is repeat-accumulate (RA) extended spatially coupled LDPC (RA-extended SC-LDPC) codes. Their base codes consist of LDPC code concatenated with RA code. Since we select rate-compatible RA component codes in base codes, the RA-extended SC-LDPC codes have rate compatibility. Moreover, the codes achieve arbitrary rate in a wide continuous real number interval, while they are capacity-approaching for various rates.

This dissertation is constituted by six chapters.

In Chapter 1, we state channel coding problem and decoding theoretical limit of two channel models. The basic concept of spatial coupling technique are also mentioned. Furthermore, we briefly introduce our basic idea and main research results of this Ph.D. work.

In Chapter 2, we introduce some basic elements of channel codes, including concept of graph based codes, structure method, decoding algorithm, and analysis instruments. The details of spatial coupling technique are also introduced by describing conventional SC-LDPC codes. The work in this dissertation is based on these elements.

The Chapters 3, 4, and 5 are the center parts of this dissertation.

In Chapter 3, we mainly introduce our proposed SC-RCC codes. The SC-RCC codes are obtained by spatially coupling multiple identical base codes that consist of repeater-combiner outer code and convolutional inner code. In base code, both outer and inner component codes have simple encoder realization. With *a priori* posteriori (APP) decoder, the convolutional inner codes with infinite impulse response can provide more effective decoding. Thus, the SC-RCC codes also have simple encoder and effective decoder. The decoding analysis with infinite code length shows that the SC-RCC codes are capacity-approaching and can resist stronger noise than conventional spatially coupled codes on additive white Gaussian noise channels (AWGNC). With finite code length realizations, the SC-RCC codes still perform better than conventional codes. It should be emphasized that with finite code length, our proposed codes still have decoding performance near to their theoretical limits, while the most of conventional spatially coupled codes are far away from the limit.

In Chapter 4, we apply our proposed SC-RCC codes to Gaussian MAC. At receiver, an iterative detection-decoding processor is used to rebuild information of transmitters. We analyze iterative detection-decoding performance with infinite code length and simulate code realizations with finite code length. The numerical results show that the SC-RCC codes perform better than conventional spatially coupled codes on Gaussian MAC.

In Chapter 5, we introduce our proposed RA-extended SC-LDPC codes for rate-compatible communication problem. A family of rate-compatible codes consists of a set of member codes with different rates, in which the higher rate member codes are embedded into the lower rate codes, and all the member codes can be processed by a single encoder and a single decoder. The design problem of rate-compatible is to guarantee all of these embedded member codes can be capacity-approaching. We structure RA-extended SC-LDPC codes by coupling multiple identical serially-concatenated base codes, which consist of LDPC outer code and a simple rate-compatible RA inner code. The base codes provide simple encoder construction and rate compatibility. Spatial coupling technique make all member codes are capacity-approaching. A potential threshold analysis is used to base codes. The fact that the potential thresholds with various rates are near to theoretical limits means the proposed codes with various rate have decoding performance near to theoretical limit. This is confirmed by analysis results of the coupled codes. Compared with conventional rate-compatible codes based on spatial coupling, our codes achieve arbitrary rates in a wide continuous real number interval and perform better than conventional rate-compatible SC-LDPC codes in the low rate region.

In Chapter 6, conclusion of the dissertation is given. By spatial coupling of serially-concatenated codes, we obtain SC-RCC codes and RA-extended SC-LDPC codes. The SC-RCC codes have decoding performance near to theoretical limit of point-to-point communication channel and MAC. Their decoding performance with finite code length may satisfy the practical requirements of communication systems. The RA-extended SC-LDPC codes are excellent rate-compatible codes that are capacity-approaching at arbitrary rates.