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DESIGN AND IMPLEMENTATION OF LDPC DECODING ALGORITHM FOR 5G SYSTEM

Abstract
for a Master's Degree
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INTRODUCTION

With the increasing demand for high-speed services in the fifth generation of mobile communication systems (5G), new channelcoding schemes are expected to provide significant performance gain for 5G key performance parameters. The 3rd Generation Partnership Project (3GPP) needs to evaluate coding gain, rate-compatible, hardware implementation, latency and throughput in the discussions of channel coding techniques of 5G New Radio (NR). At the RAN1#87 conference, the Low Density Parity Check (LDPC) codes with various advantages become the channel coding scheme of the data channel to replace Turbo codes for the enhanced Mobile Broadband scenario, and then, the encoding and decoding algorithms and decoder design of LDPC codes have become the focus, they have wide application values and significant economic benefits.

This thesis summarizes the development of LDPC codes and analyzes the advantages and characteristics of LDPC codes in the evaluation of channel coding schemes in 5G technical specifications. The definition and coding method of LDPC codes are introduced based on the check matrix and graph model of LDPC codes. The parameters affecting the error correction performance are analyzed, and the structural characteristics of the block LDPC codes benifiting hardware implementation are summarized. This thesis studies the special structure of the check matrix for 5G NR LDPC codes and discusses the generation method. In addition, the advantages of flexible scalability and rate compatibility of 5G LDPC codes are analyzed.

This thesis focus on the Belief Propagation (BP) algorithm of LDPC, and discusses the iterative decoding processes of BP algorithm with different measures based on the Tanner graph. In order to reduce complexity, the evolutions of approximation algorithms such as Min-Sum algorithm and Normalized Min-Sum algorithm are discussed, and then the low complexity Density Evolution single minimum Min-sum (DE-smMS) algorithm was proposed. The proposed algorithm combines the density evolution theory with the weighted average scheme to correct the normalization factor in the iterative process and then calculates a single minimum value to reduce the complexity. The simulation results show that the proposed algorithm has a performance gain of about 0.2dB compared with the existing single minimum algorithm, especially, when the code rate is low, the proposed algorithm can achieve the same performance as the NMS algorithm. The proposed algorithm achieves a better trade-off between complexity and decoding performance.

Based on the block structure characteristics of 5G NR LDPC codes, the corresponding Layered scheduling scheme is proposed. The design and implementation of the transmitter and receiver of the physical downlink shared channel were completed based on TMS320C6678 DSP platform, and the design was verified to be consistent with the technical specification of 5G NR on signal&spectrum analyzer of Rohde&Schwarz. The implementation of LDPC decoder is completed, and the implementation architecture of a parallel decoder is proposed for the proposed DE-smMS algorithm. The 5G Physical Downlink Shared Channel is implemented on the DSP to analyze the error correction performance and the latency of the decoder. The parallelism of the decoder is implemented on the C6678 with the OpenMP framework based on multi-core shared memory. The results show that the correction performance of the proposed algorithm approximates the traditional NMS algorithm and the latency is reduced by about 12 %.

GENRAL DESCRIPTION OF WORK

Relevance of the subject

The work corresponds to paragraph 1 «Digital information and communication and interdisciplinary technologies, production based on them» of the State Program of innovative development of the Republic of Belarus for 2021–2025.

The work was carried out in the educational institution Belarusian State University of Informatics and Radioelectronics within the framework of research work 21-2033 "Processing, coding and transmission of information in network-centric systems".

The aim and tasks of the work

The LDPC code, proposed by Gallager in 1962, has an error correction performance close to the Shannon limit when using an iterative decoding algorithm, which is not only lower in decoding complexity than Turbo code, but also facilitates parallelized hardware implementation and has a peak throughput beyond Turbo code. These advantages correspond to the high throughput and flexibility requirements of 5G NR, which prompted 3GPP to use LDPC code instead of Turbo code as the channel coding scheme for data channels in 5G eMBB scenarios. The compilation code principle of LDPC code in 5G communication system is studied. The structural features of 5G NR LDPC and its rate-compatible flexibility are analyzed, and the LDPC decoding algorithm and DSP implementation are studied in depth.

To achieve this aim, the following tasks were solved in the dissertation:

1 The basic definition and coding method of LDPC codes are discussed based on the checksum matrix representation and Tanner diagram model of LDPC codes, focusing on the parameters affecting the error correction performance of LDPC codes and the structural characteristics of block LDPC codes for hardware implementation. The special structure of 5G NR LDPC code checksum matrix and its generation method are described, and its excellent performance in terms of flexible scalability and rate compatibility is analyzed.

2 Based on the Belief Propagation (BP) decoding algorithm of LDPC codes, the iterative decoding process of BP algorithm with different measures is studied from Tanner graph. In the aspect of low complexity, the evolution process of BP algorithm to the approximation algorithms such as Min Sum and Normalized Min Sum (NMS) is derived in detail, and on this basis, the Density Evolution single minimum Min-sum (DE -sm MS) algorithm is proposed. The normalization factor in the iterative process is modified by combining the density evolution theory and the weighted average scheme, and the complexity is reduced by using the single minimum calculation. Simulation results show that the proposed algorithm has a performance gain of about 0.2 dB over the existing single minimum algorithm and is comparable to the NMS algorithm at lower code rates, demonstrating the advantages of the proposed algorithm in terms of compromise complexity and decoding performance.

3 The corresponding Layered scheduling scheme is given for the characteristics of the chunked structure of the 5G NR LDPC code check matrix, and the advantages of its parallel implementation are analyzed in detail. Based on TMS320C6678 DSP development platform, the design and implementation of 5G Physical Downlink Shared Channel (PDSCH) transmitter and receiver are completed, and the conformance of the design with 5G NR technical specifications is verified by Rode's signal spectrum analyzer. The parallel LDPC decoder implementation architecture is proposed for the DE-smMS algorithm, and the error correction performance and decoding latency of the decoder are analyzed by the DSP implementation of 5G PDSCH, and the parallelism of the decoder is implemented on C6678 using the Open MP framework based on multicore shared memory. The implementation results demonstrate that the proposed algorithm achieves an error correction performance close to that of the conventional NMS algorithm and reduces the decoding latency by about 12 %.

Personal contribution of the author

The content of the paper reflects the individual contributions of the authors. It includes algorithm improvement, conducting experiments, comparing with existing algorithms, processing and analysing results, and formulating conclusions.

Testing and implementation of results

The main provisions and results of the dissertation work were reported and discussed at: International scientific and technical seminar "Technologies of information transmission and processing" (Minsk, March, 2022) and International scientific and technical seminar "Technologies of information transmission and processing" (Minsk, March, 2022) and International scientific and technical seminar "Technologies of information transmission and processing" (Minsk, May, 2023) and 59th scientific conference of postgraduates, undergraduates and students, (Minsk, May, 2023)

Author's publications

A-1 Liu FangYu. NR LDPC in 5G mobile communication system / Liu FangYuGao, Salomatin S B. // Технологии передачи и обработки информации (Technologies of information transmission and processing): материалы Международного научно-технического семинара, Минск, март – апрель 2023 г. – Minsk : BSUIR, 2023. – С. 23–26.

A-2 Liu FangYu. Analysis and simulation based 5G channel coding technologyNR / Liu FangYuGao, Salomatin S B. // Технологии передачи и обработки информации (Technologies of information transmission and processing): материалы Международного научно-технического семинара, Минск, март – апрель 2023 г. – Minsk : BSUIR, 2023. – С. 50–53.

Structure and size of the work

The dissertation work includes an introduction, an overview of related work, proposed algorithms, experimental results, conclusion, and bibliography.

The total volume of the thesis work is 89 pages, including 84 pages of text, 36 figures, 5 tables, a list of bibliographic sources used, and a list of author's publications on the topic of the thesis.

Plagiarism

An examination of the dissertation « DESIGN AND IMPLEMENTATION OF LDPC DECODING ALGORITHM FOR 5G SYSTEM» by Author's Full Name was carried out for the correctness of the use of borrowed materials using the network resource «Antiplagiat» (access address: https://antiplagiat.ru) in the online mode 22.05.2023. As a result of the verification, the correctness of the use of borrowed materials was established (the originality of the thesis is 82.47 %)

SUMMARY OF WORK

In Chapter 1, this thesis introduces the relevant concepts: in Section 1.1, the paper presents the 5G background and the related parameters. In Section 1.2, this thesis details the scheme for 5G NR channel coding, as well as in Section 1.3, this thesis details the current development and status of LDPC codes.

The LDPC code was proposed in 1962 and the （N, K） LDPC code defined on the binary domain GF(2) is a linear packet code that can be represented by a check matrix H of dimension $M \times N$ and a Tanner diagram. As a linear packet code, the code word generated by LDPC code consists of K bits of information and $M = N \times K$ bits of check bits when coding the channel. LDPC code is characterized by a sparse check matrix H, which greatly reduces the complexity of the iterative decoding algorithm compared with other linear packet codes and is the main reason for its advantage in practical applications. Since this paper mainly discusses 5G NR LDPC codes, the subsequent LDPC codes are mainly binary non-regular LDPC codes.

In Chapter 2, the coding principle and graph model of LDPC codes are described specifically.

Matrix representation of LDPC code

$$\begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1N} \\ h_{21} & h_{22} & \cdots & h_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{MN} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = 0$$

Tanner diagram representation of LDPC code

Suppose that a regular LDPC code can also be represented as an LDPC code when its degree is 2, with a code rate of, the check matrix and the corresponding Tanner diagram are shown Figure 1

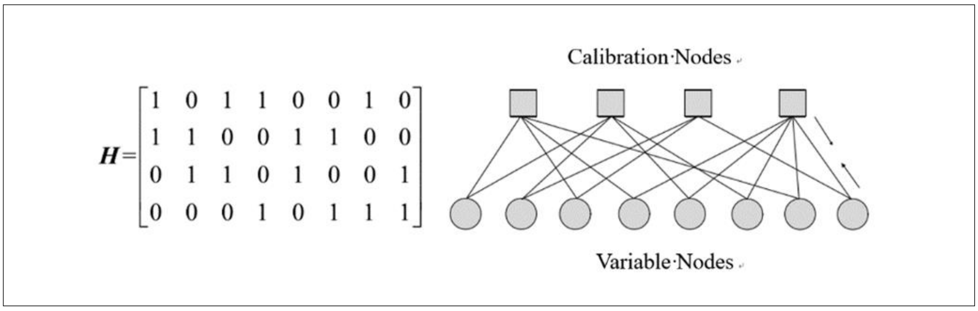

Figure 1 – Checksum matrix and Tanner diagram of LDPC code

In Chapter 3, the LDPC code decoding algorithm and density evolution theory are described.

BP decoding algorithm decoding process are shown Figure 2.

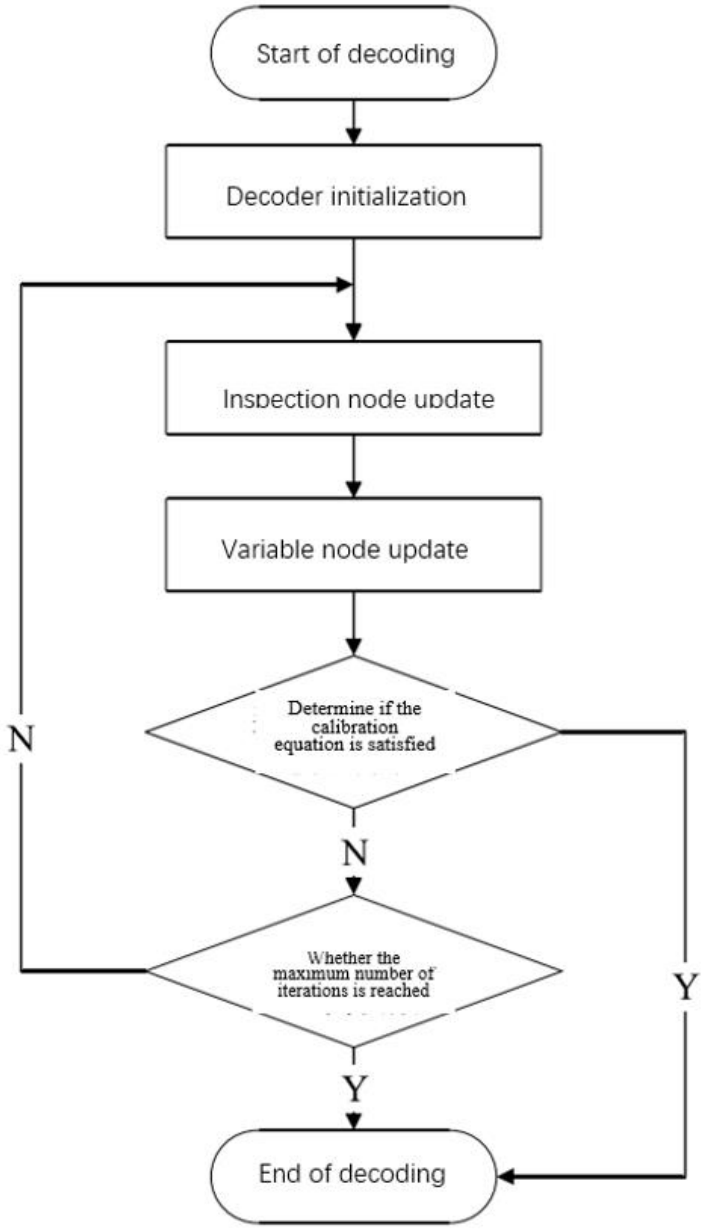

Figure 2 – BP decoding algorithm decoding process

BP algorithm for probability measures

On the probability measure, the input to the BP decoding algorithm is the posterior probability, where the V2C and C2V probability messages delivered by the nodes are denoted as $q_{n\to m}$, and $r_{m\to n}$, where:

$$q_{n\to m}(0) = P_{X|Y}(x_n = 0 \mid y_n)$$

$$q_{n\to m}(1) = P_{X|Y}(x_n = 1 | y_n)$$

where x_n –Sending code words;

y_n –Receive code words;

Approximation algorithm for LDPC: MS Algorithm

MS algorithm, also known as BP-Based algorithm, is still LLR-BP algorithm in essence, which reduces the complexity by replacing the hyperbolic tangent function computation required for check node update in BP algorithm by approximation.

When using LLR message values, the random variable calculation proposed by Gallager in the literature [11] can be expressed as: $L(U \oplus V) = sign(L(U))sign(L(V)) f(f|L(U| + f(|L(V)|))$, where the pairwise transformation function $f(\bullet)$ is defined as $f(x) = \log(e^x + 1)/(e^x - 1)$, that is, the presence of $f(f(x)) = x$, Since the function $f(x)$ is monotonically decreasing, the derivation can be obtained as shown

$$\begin{aligned} |L(U \oplus V)| &= f(f(|L(U)|) + f(|L(V)|)) \\ &\le f(f(\min\{|L(U)|,|L(V)|\})) \\ &\le \min\{|L(U)|,|L(V)|\} \end{aligned}$$

In Chapter 4, the DSP implementation of the 5G NR LDPC code is discussed. First, the TMS320C6678 DSP development platform is briefly introduced, including its OpenMP framework for multi-core parallel application development. Then the transmitter and receiver processing flow design of 5G NR data channel is reviewed, and the parallel decoder architecture of 5G NR LDPC code is proposed. The DSP implementation of 5G PDSCH is completed using C language, and the parallel implementation of the decoder is completed using OpenMP. Finally, the performance and decoding delay of the LDPC decoder are analyzed. The unctional block diagram of TMS320C6678 DSP is shown Figure 3, data Channel Sender Processing flow is shown Figure 4 and 5G PDSCH Receiver Design Flow is shown Figure 5.

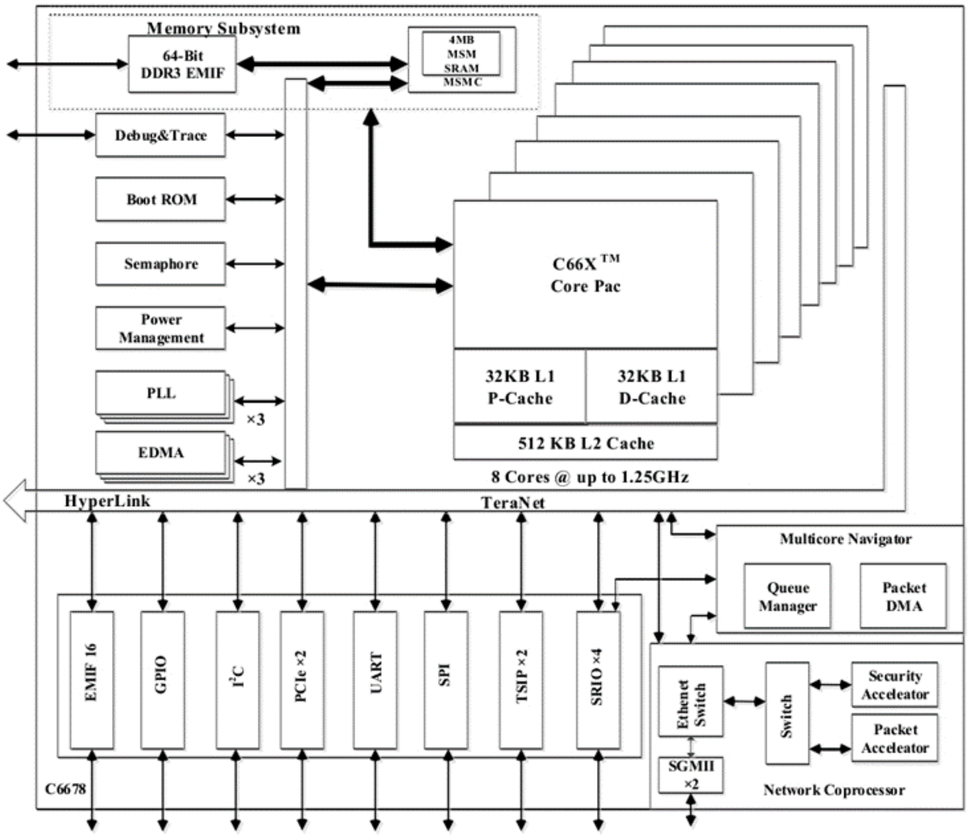

Figure 3 – Functional block diagram of TMS320C6678 DSP

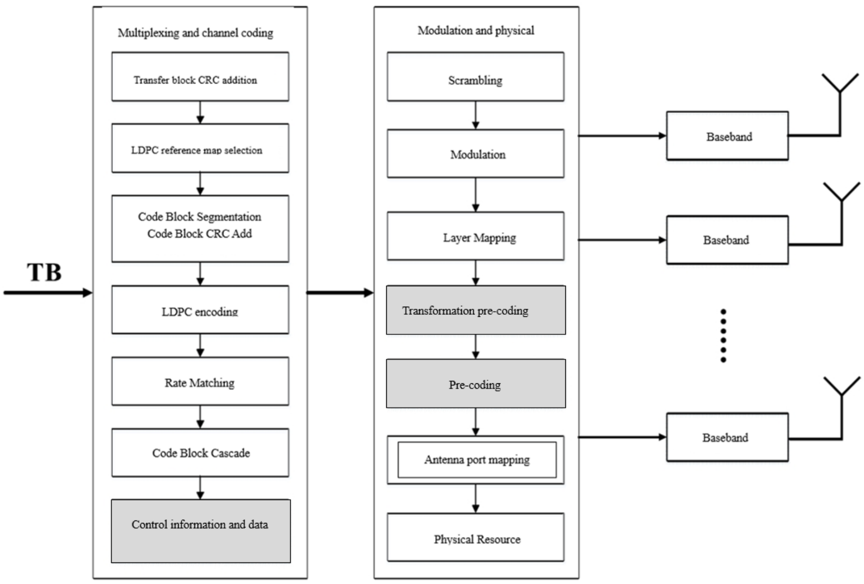

Figure 4 – Data Channel Sender Processing Flow

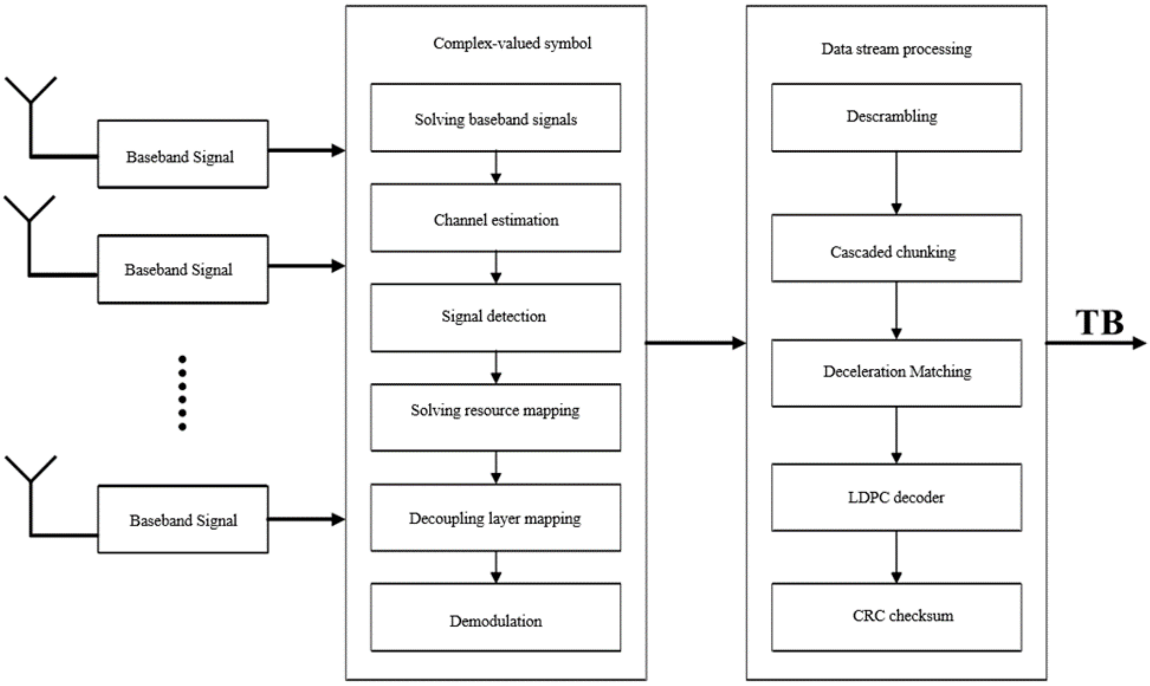

Figure 5 – 5G PDSCH Receiver Design Flow

Since there are many parameters involved in the 5G PDSCH implementation, only the LDPC decoder related parameters are described in this section. Figure 6 and Figure 7 show the (Frame Error Rate, FER) performance of 5G NR LDPC codes with code rate , and under PDSCH using the NMS and DE-smMS algorithms, respectively (the code rate settings are different from the MCS configuration table in the 3GPP specification). The base map is the coded message length, and the maximum number of decoder iterations is set to 30. QPSK modulation is chosen to generate the baseband signal and then pass through the AWGN channel.

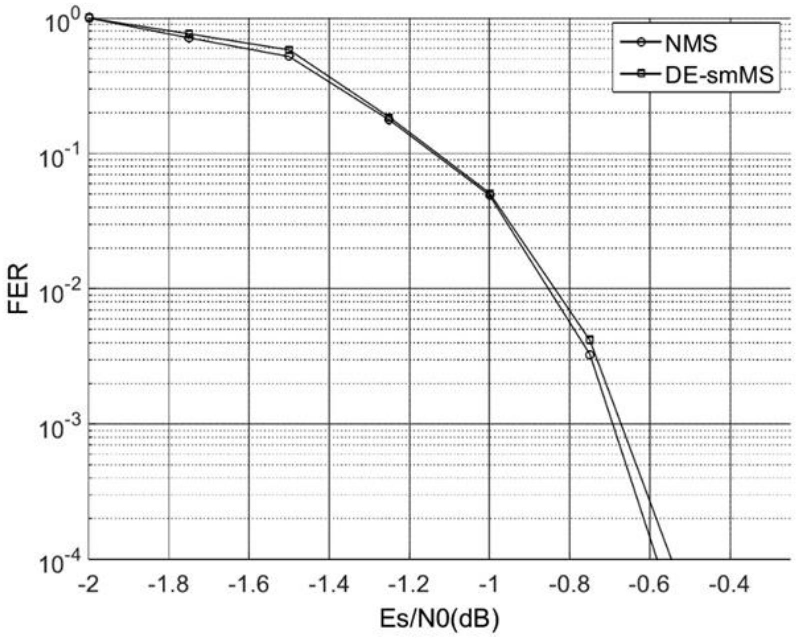

Figure 6 – Comparison of FER performance of DE-smMS algorithm and NMS algorithm ($R = 1/3$)

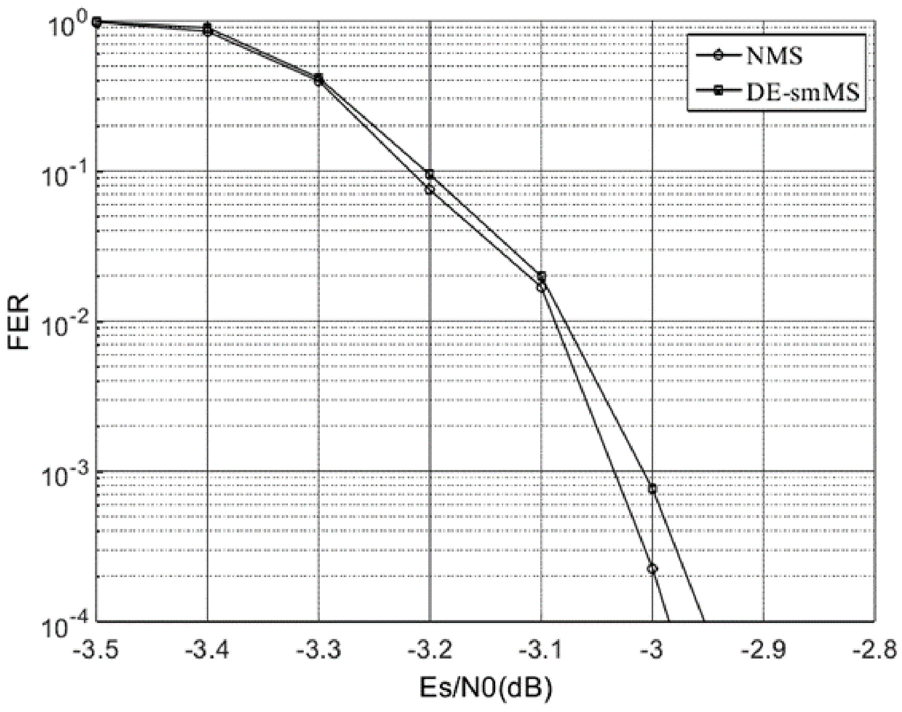

Figure 7 – Comparison of FER performance of DE-smMS algorithm and NMS algorithm ($R = 2/3$)

CONCLUSION

The LDPC code, proposed by Gallager in 1962, has an error correction performance close to the Shannon limit when using an iterative decoding algorithm, which is not only lower in decoding complexity than Turbo code, but also facilitates parallelized hardware implementation and has a peak throughput beyond Turbo code. These advantages correspond to the high throughput and flexibility requirements of 5G NR, which prompted 3GPP to use LDPC code instead of Turbo code as the channel coding scheme for data channels in 5G eMBB scenarios. In this paper, the compilation code principle of LDPC code in 5G communication system is studied in the context of the National Science and Technology Major Project "Enhanced Mobile Broadband 5G Terminal Emulator Research and Development" (No. 2017ZX03001021-004). The structural features of 5G NR LDPC and its rate-compatible flexibility are analyzed, and the LDPC decoding algorithm and DSP implementation are studied in depth. The main contributions and innovations of the whole paper can be summarized as follows:

1 The matrix representation and Tanner graph representation of LDPC codes are analyzed in depth, and the effects of the degree distribution of LDPC codes and the existence of loops in the graph model on their error correction performance are reviewed.

2 The structured composition of the QC-LDPC code and the advantages of the chunked structure in parallelization implementation are discussed. A detailed analysis of the structural features of 5G NR LDPC codes and their generation methods, the flexibility of its checksum matrix expansion and the support of 5G rate compatibility are described.

3 The BP decoding algorithm of LDPC codes and its approximation algorithm are studied in depth, and the evolution of the improved algorithm in the complexity direction is derived in detail. A low-complexity DE-smMS algorithm is proposed, which combines density evolution theory and weighted averaging scheme to calculate the normalization factor in the algorithm accurately, and reduces the computational complexity in the iterative process by single-minimum calculation. The simulation results demonstrate that the proposed algorithm has a performance gain of about 0.2 dB compared with other single-minimum algorithms, which is closer to the traditional NMS algorithm.

4 A Layered scheduling scheme is proposed for 5G NR LDPC codes to provide algorithmic support for the implementation of parallel decoder. Simulation results show that the performance gain of about 0.5dB can be achieved by using this scheduling scheme compared with the conventional Flooding scheduling.

5 The features of TMS320C6678 DSP platform are described, and the main processing flow of 5G data channel is given. A parallel decoder architecture for 5G NR LDPC codes is proposed based on the proposed DE-smMS algorithm. In this paper, the 5G PDSCH transmitter and receiver are developed on C6678 DSP using C language, and the advantages of parallel LDPC decoder are realized by combining the OpenMP framework and the features of multi-core DSP. In addition, this paper verifies the conformance of the PDSCH design with the 5G NR specifications by using a Rhodes signal spectrum analyzer.

LIST OF AUTHOR'S PUBLICATIONS

A-1 Liu FangYu. NR LDPC in 5G mobile communication system / Liu FangYuGao, Salomatin S B. // Технологии передачи и обработки информации (Technologies of information transmission and processing): материалы Международного научно-технического семинара, Минск, март – апрель 2023 г. – Minsk : BSUIR, 2023. – С. 23–26.

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