FORMATION OF EXTENDED MODULATION CODE SCHEMES BASED ON THE LDPC CODEC 5G NR

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In modern wireless communication systems, adaptive coding and modulation are used to ensure high spectral efficiency and error correction. This paper examines a modification of coding schemes based on the LDPC codec for 5G NR communication systems. The goal of the study is to extend the range of coding schemes for different signal-to-noise ratios (SNR) in adaptive modulation and coding. This is achieved by adjusting the lifting factor (Zc) and expanding the LDPC code rate range from 10/1024 to 1000/1024. The coding schemes also propose using a wider range of modulation schemes, including up to 4096-QAM, which increases the spectral efficiency of data transmission. The work relies on mathematical simulations using the Monte Carlo method to evaluate the bit error rate (BER) as a function of the SNR for various combinations of coding schemes. Both the combinations specified in the 5G NR standards and those proposed in this study are considered. A threshold SNR level is identified for each parameter combination, at which the communication system can ensure a bit error probability that does not exceed the threshold value. The dependencies of achievable spectral efficiency on SNR are obtained. The results of the study demonstrate an expanded operational SNR range compared to 5G NR, within which the communication system remains functional. The proposed solution improves spectral efficiency at low noise levels and enables data transmission at low speeds under high noise conditions, where the schemes specified in 5G NR standards are unable to maintain communication. The results of this research can be applied to various telecommunications systems, including mobile networks, the Internet of Things (IoT), unmanned aerial vehicles (UAVs), and radio relay communication lines.

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Introduction

Wireless communication systems are evolving and require increasingly efficient and reliable data transmission methods, especially under conditions of high interference and noise levels. Error-correcting coding plays a crucial role in ensuring the quality and speed of data transmission.

One of the most effective methods of error-correcting coding is Low-Density Parity-Check (LDPC) codes. These codes were first proposed by Robert Gallager in 1960 [1], but remained underutilized for several decades due to their high computational complexity. Thanks to the development of computing technology and the efforts of researchers like Tanner [2], McKay [3, 4] and Radford [4], LDPC codes began to be applied in practice in the early 21st century, becoming an important part of modern communication systems. They have proven to be effective in error correction, providing high reliability in data transmission.

Currently, LDPC codes are among the most efficient and are applied in standards such as 5G NR [5], Wi-Fi (IEEE 802.11be) [6], DBW-T2 [7], DBW-S2 [8], etc. Comparing LDPC codes with Reed-Solomon codes, turbo codes, and others, we can conclude that, in general, they provide a higher level of error correction [9].

LDPC codes are linear block codes that utilize binary matrices in both encoding and decoding procedures. A distinguishing feature of LDPC codes is their sparse matrix structure, where most elements are zeros. This sparsity reduces the computational complexity of encoding and decoding processes.

During data transmission, communication systems face various scenarios where the levels of noise and interference may vary significantly. In such cases, it is important to have versatile error-correcting code solutions capable of operating effectively across a wide range of signal-to-noise ratios (SNR). Modulation and Coding Schemes (MCS) are tools that allow for adaptive operation in different conditions. These schemes represent tables with modulation and coding parameters that depend on channel state information (CSI) and are used to optimize data transmission. The system dynamically selects the most appropriate transmission parameters from MCS tables, taking the SNR in the channel into account and allowing it to adapt to different conditions.

In the 5G NR system, modulation code schemes are described in detail in the 3GPP TS 38.214 specification [10]. Within this specification, various combinations of modulation and encoding rates are already provided, which can adapt to the state of the channel.

In recent years, a large number of studies have been conducted on the topic of LDPC codes. Some of them are also aimed at improving MCS and adaptive modulation, and encoding in 5G networks. For example, the article [11] explores machine learning methods for predicting MCS in systems with OFDM (Orthogonal Frequency Division Multiplexing), which allows to increase spectral efficiency. The article [12] examines models of multichannel communication in 5G NR systems using mixed sets of basic physical level parameters (numerologies), which allows us to understand how different numerologies can affect the performance of MCS.

In addition, the article [13] explores the use of reinforcement learning methods for adaptive modulation and coding, which allows the base station to select the appropriate MCS to maximize spectral efficiency with low error levels. The article [14] discusses in detail the technical aspects of MCS in the 5G NR standard, including the use of LDPC codes for data channels. However, the existing works do not address the issues of communication system operation in a wide range of signal-to-noise ratios. Also, the issues of expanding the MCS by increasing the scaling parameters, encoding speeds, codeword lengths and modulation indices are not considered, which is the subject of research in this article.

The modification of 5G NR modulation code schemes proposed in this paper extends the SNR range for adaptive modulation, which can be applied not only in 5G NR but also in other communication systems.

The extended set of encoding and modulation parameters is useful in high-noise communication channel scenarios where higher spectral efficiency is required. For instance, under low signal-to-noise ratio (SNR) conditions, LDPC codes can be applied at ultra-low rates, which increases redundancy and enhances error correction capabilities. Under high SNR conditions, higher rate codes can be used to boost system throughput.

Additionally, the paper addresses the construction of LDPC codes in accordance with the 5G NR standard, as well as the noise immunity and spectral efficiency provided by both the standard and the proposed methods.

LDPC codes in 5G NR

According to Shannon's theory, increasing the codeword length enhances data transmission resilience to interference and noise. However, for linear block codes, this also results in larger matrix sizes and longer syndrome vectors, complicating the encoding and decoding processes and requiring more memory and computational resources. The solution to this challenge is to use sparse matrices, which can be stored more efficiently in memory. For instance, only the positions of the non-zero elements, which are much fewer in sparse matrices, can be stored in the device's memory. In this context, quasi-cyclic LDPC (QC-LDPC) codes are particularly noteworthy. These codes form a distinct class of LDPC codes, characterized by a specific structure of the parity-check matrix, which optimizes storage and computation during encoding and decoding procedures. QC-LDPC codes leverage cyclic shift operations, enabling scalability by generating codewords of varying lengths. The application of LDPC codes in 5G NR is based on the specification [5].

The 5G NR standard defines the use of various types of the quadrature amplitude modulation (QAM): π/2-BPSK, QPSK, 16QAM, 64QAM, 256QAM, and 1024QAM, with the choice depending on transmission conditions. The code rate for LDPC within the 5G NR standard can range from 30/1024 to 948/1024. The combination of modulation schemes and corresponding LDPC code rates is selected based on the communication conditions. For example, to transmit critical data requiring higher error protection, lower-order modulations with higher redundancy are used (e.g., a code rate of 30/1024). Under favorable conditions, more complex modulation schemes, such as 256QAM or 1024QAM, are employed with minimal redundancy (code rate of 948/1024). This adaptive approach allows the system to respond flexibly: when the channel is unstable, reliability is prioritized, whereas under optimal conditions, the focus shifts to throughput. In combination with appropriate modulation schemes, this provides spectral efficiency from 0.0586 bits/s/Hz to 9.2578 bits/s/Hz.

The parity-check matrix **H** of LDPC codes in 5G NR is constructed based on two base graphs (BG): BG1 and BG2, described in [15]. These graphs differ in structure and purpose: BG1 is optimized for longer codewords and provides higher error-correcting capability, while BG2 is better suited for shorter codewords. The dimensions of BG1 are 46x68, and BG2 are 42x52 elements, respectively. The construction of the **H** matrix follows a procedure involving cyclic shift and expansion. A key aspect of these procedures is the selection of the *iLS* set and the *Zc* expansion factor. The full structure of the parity-check matrix generation process is detailed in [5], and due to the described approach, both matrix construction and encoding are significantly simplified. The process can be reduced to adding elements of the original information sequence with a certain shift. This procedure replaces the traditional matrix multiplication of the original sequence by the generator matrix G, as used in conventional block codes [15]. In addition, the **H** matrices based on BG1 and BG2 support HARQ (Hybrid Automatic Repeat Request) technology. If errors occur during transmission, the system requests the missing packets and combines them with the already received data. This is especially important in low-latency modes, such as URLLC (Ultra-Reliable Low-Latency Communication).

In URLLC scenarios, where high reliability and low latency are required, LDPC codes with short codewords and high redundancy may be used. Specialized base graph configurations and *Zc* parameters are provided for these tasks, ensuring fast data processing.

A simplified diagram of the communication channel model with LDPC encoding according to 5G specifications is shown in Figure 1. It consists of such blocks as: CRC encoding, segmentation, LDPC encoding, rate equalization, modulation, communication channel. Reverse demodulation and decoding procedures are performed in the receiver.

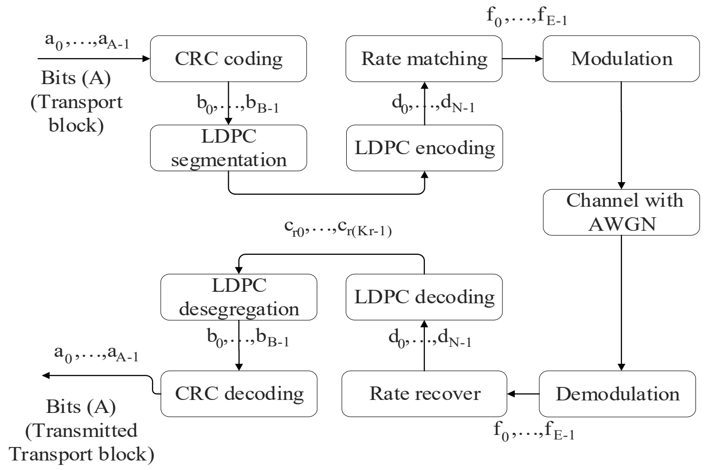

Fig. 1. Diagram of a communication channel model with LDPC encoding

In the 5G NR standard, Cyclic Redundancy Check (CRC) encoding ensures data integrity by adding a checksum to detect bit errors during transmission. At the output of the CRC encoding block, a code block is formed containing the source data and the CRC checksum. Segmentation is necessary to divide large data blocks into smaller segments, which can then be encoded independently based on the selected base graph (*BG*) and the expansion factor *Zc*. The *Zc* parameter adjusts the size of the codewords depending on the transmission conditions. At the output of the segmentation block, individual segments (**C**) of code blocks with a length of (*K*) are obtained. Each segment can then be encoded independently, enabling parallel processing and increasing the overall system throughput.

After the segmentation block, the information packets are sent to the main block of the scheme – LDPC encoding. The first step in this block is the generation of the parity-check matrix **H**, based on the base graph (BG1/BG2), scaling factor *Zc*, and *iLS* coefficient. Next, parity bits are added to the information bits of each code block, according to matrix **H**. It should be noted that the first *2 Zc* bits of each codeword are not transmitted, saving bandwidth, as they will be restored on the receiving side.

After coding, the codeword is generated with a specific mother code rate, which is fixed and corresponds to 1/3 for BG1 and 1/5 for BG2. This rate is determined by the initial encoder parameters and defines the original ratio between information and parity bits.

The rate matching block adapts the codeword to the required size, ensuring the desired code rate by excluding, duplicating, or adding parity bits. This is how the code rate adjustment process takes place.

Next, the bits are sent to the QAM modulation unit, where modulation symbols are mapped onto orthogonal subcarriers to form the OFDM symbol. The last two steps in the model diagram are omitted, as they do not affect the error-correcting capability of the LDPC codec.

The generated QAM symbols are transmitted through a communication channel with additive white Gaussian noise (AWGN) and then passed to the receiver's soft decision demodulator. In this block, estimates are formed in the form of log-likelihood ratios (LLR). The 5G NR rate recovery block adjusts the received vector to the correct length for proper LDPC decoding. Missing bits are filled with zero LLR values to avoid data distortion. If a bit was transmitted multiple times (e.g., through HARQ), their LLR values are summed to improve reliability. The resulting vectors from this procedure are passed to the LDPC decoding block.

There are various decoding algorithms, such as sum-product [16], min-sum [17], bit-flipping [18], and others. Generally, all decoding algorithms can be divided into "hard-decision" and "soft-decision" algorithms. An example of the former is the bit-flipping algorithm, the concept of which, like the sum-product, was originally proposed by Gallager in [1]. Hard-decision algorithms are simpler in their operation, while soft-decision algorithms, using a probabilistic approach to bit representation, allow for greater error-correcting capability of the code.

Each decoding method has its pros and cons. One of the most widely used methods is the sum-product algorithm, which provides high decoding accuracy but uses hyperbolic functions in its operation, significantly complicating its process. The min-sum family of algorithms operates with simpler comparison and multiplication operations, but the decoding accuracy is reduced as a result.

In most cases, the decoding procedure is based on a probabilistic approach and LLR recalculation according to the structure of the parity-check matrix. This process is performed iteratively until the maximum number of iterations is reached or early stopping conditions are met. In each decoding iteration, a syndrome is calculated – a vector indicating whether the parity-check equations are satisfied for the current state of the decoded code. If the syndrome equals zero, it indicates that the current code vector satisfies all parity-check equations and thus is likely already correct. When this condition is met, the decoding process can terminate early. The output of the LDPC decoder forms a corrected vector of information bits.

The desegmentation block's task is to combine the vectors that arrived after LDPC decoding into a single information packet. The integrity of the transmitted information packet is checked using CRC decoding.

Modification of LDPC codes and modulation code schemes

The proposed modification of LDPC codes involves controlling the scaling parameter (Zc) and the code rate. Adjusting Zc within the range from 2 to 768 allows the formation of codewords with a length of N = 50688 bits instead of the standard value of N = 25344 bits [5], which increases flexibility in frame formation. This modification expands the coding rate range from 10/1024 to 1000/1024, compared to the standard rates from 30/1024 to 948/1024.

Furthermore, the modified approach supports the use of various modulation schemes, ranging from QPSK to 4096-QAM, unlike standard solutions that are limited to 1024-QAM modulation [5]. This increases channel bandwidth and can be applied in communication systems operating under conditions characterized by high signal-to-noise ratio values (over 30 dB).

Modifying the coding rate and modulation parameters enables new combinations of MCS. Figure 2 shows the values of the modulation order and coding rate that make up the MCS. The modified table includes 62 configurations, 50 of which are described in the 5G NR standard [5].

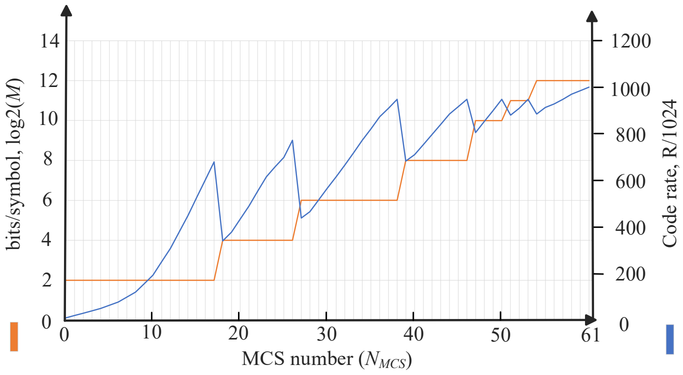

Fig. 2. Graph of the dependence of the modulation index and encoding rate on the MCS

Figure 2 shows in orange the value of the number of bits per $\log_2(M)$ symbol (M – is the modulation index) for each MCS with the number N_{MCS}, and in blue the corresponding code rate R (the values displayed on the right axis must be divided by 1024). The MCS values outside the range 3-51 correspond to the extended parameters, and the values within this range correspond to the standard parameters of the MCS 5G table [4]. The final MCS table can be derived from the dependencies shown in Figure 2, in accordance with the structure presented in Table 1, as N ranges from 0 to 61.

Table 1

Row structure of the modified MCS table

N_{MCS}	$\log_2(M)$	$R/1024$

Simulation results of the proposed codec

For each modulation and code rate in the LDPC-encoded channel, the BER (Bit Error Rate) dependency on SNR was derived, as shown in Figure 3. The dependencies were obtained using the Monte Carlo simulation method, in accordance with the communication channel model shown in Figure 1, and using min-sum algorithm-based decoding.

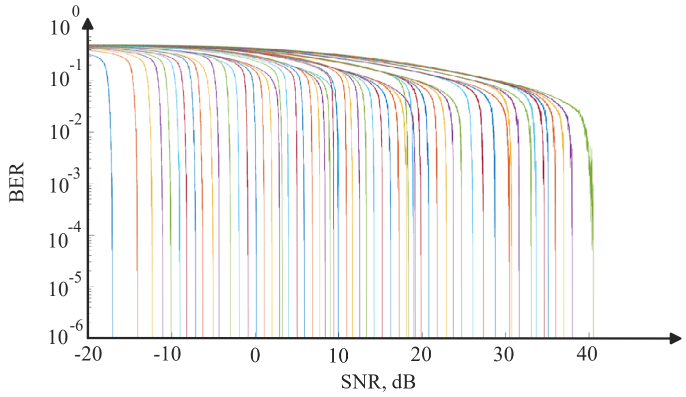

Fig. 3. Graph of the dependence of BER on SNR for each of the MCS according to the extended

For each relationship, the spectral efficiency was calculated using the formula:

$$SE = \log_2(M)\cdot R/1024$$

and the SNR Threshold level was determined, where the BER reaches 10^{-6}. The SNR Threshold value is the minimum required for using the corresponding MCS. Figure 4 shows the dependence of SE on the SNR Threshold.

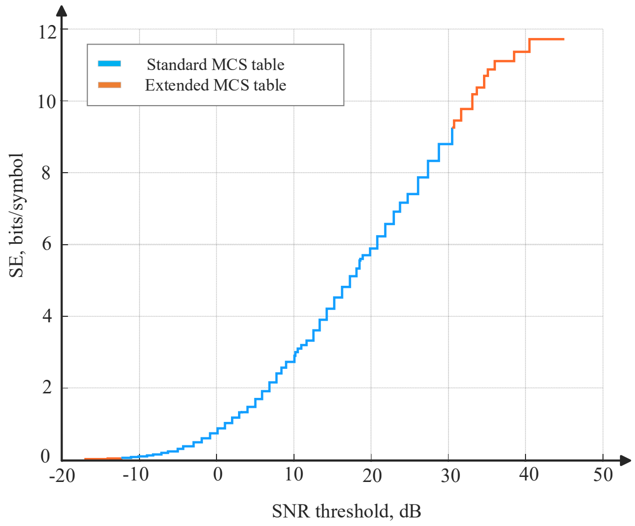

Fig. 4. Graph of the dependence of the spectral efficiency of SE on the SNR Treshold for the standard and extended MCS tables

Figure 4 shows that the proposed modified MCS table enables the communication system to operate over a wider SNR range. For instance, a communication system using LDPC with a low code rate can operate at an SNR as low as - 17.12 dB. For the standard solution described in [4], the communication system remains stable at SNR > - 12.34 dB.

Furthermore, the proposed approach allows for a higher spectral efficiency — up to 11.7188 bps/Hz. This is 20% higher than the standard spectral efficiency for 5G NR (up to 9.257 bps/Hz). However, achieving such high spectral efficiency requires a signal-to-noise ratio above 30 dB. This can only be achieved in certain channels, such as radio relay communication links (RRL).

Conclusion

In this article, a modified table of modulation code schemes for the 5G NR communication system based on the LDPC codec is proposed, and the effectiveness of its application is evaluated. The proposed modifications include increasing the codeword length by adjusting the expansion factor *Zc*, expanding the range of coding rates, and incorporating a wider set of possible modulation schemes. These changes enhance the flexibility and adaptability of communication systems to varying transmission channel conditions.

The study results demonstrate that the proposed modifications offer higher spectral efficiency and enable more reliable operation in noisy communication channels compared to the standard 5G NR configuration. This improvement is achieved by employing lower coding rates in low SNR conditions.

Thanks to its versatility, the proposed approach and the generated MCS table can be applied across various communication systems, including the Internet of Things (IoT), mobile communications, UAV communications, RLL (Radio Link Layer), and others. High spectral efficiency and the ability to meet required bit error rate (BER) thresholds make such systems relevant and competitive in the telecommunications equipment market.

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ФОРМИРОВАНИЕ РАСШИРЕННЫХ СИГНАЛЬНО-КОДОВЫХ КОНСТРУКЦИЙ НА ОСНОВЕ LDPC КОДЕКА 5G NR

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Аннотация
В современных системах беспроводной связи для обеспечения высокой спектральной эффективности и исправления ошибок используется адаптивное кодирование и модуляция. В статье рассматривается модификация сигнально-кодовых конструкций на основе LDPC кодека для системы связи 5G NR. Целью работы является расширение диапазона используемых сигнально-кодовых конструкций с различным отношением сигнал-шум при адаптивной модуляции и кодировании. Это достигается за счет изменения параметров масштабирования (Zc) и увеличения диапазона скоростей кодирования LDPC от 10/1024 до 1000/1024. В сигнально-кодовых конструкциях также предложено использование более широкого набора модуляций, вплоть до 4096-QAM, что повышает спектральную эффективность передачи данных. Работа опирается на математическое имитационное моделирование с использованием метода Монте-Карло для оценки вероятности битовой ошибки в зависимости от отношения сигнал-шум для различных комбинаций сигнально-кодовых конструкций. Рассматриваются как комбинации, приведенные в спецификациях 5G NR, так и предложенные в этой работе. Для каждой комбинации параметров определен граничный уровень отношения сигнал-шум, при котором система связи способна обеспечить вероятность битовой ошибки, не превышающей пороговое значение. Получены зависимости обеспечиваемой спектральной эффективности от отношения сигнал-шум. Результаты исследования демонстрируют расширение диапазона значений отношения сигнал/шум по сравнению с 5G NR, при которых система связи остается работоспособной. Предложенное решение позволяет повысить спектральную эффективность при низком уровне шума, а также обеспечить передачу данных с низкой скоростью при высоком уровне шума, в условиях, при которых конструкции, приведенные в спецификациях 5G NR, не способны поддерживать связь. Результаты исследования могут быть использованы в телекоммуникационных системах различного назначения: мобильные сети, интернет вещей, беспилотные летательные аппараты и радиорелейные линии связи.

Ключевые слова: *LDPC кодирование, 5G NR, помехоустойчивое кодирование, адаптивная модуляция, кодовая скорость, спектральная эффективность, сигнально-кодовые конструкции (MCS).*

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