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Research on different channel coding methods for 5G communication

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Abstract: The implementation of channel coding techniques has the potential to yield coding gains, augment the capacity of the communication system, and significantly enhance the performance of the communication system. The quest for a code possessing a channel capacity surpassing the Shannon limit has been a longstanding pursuit among researchers. The utilization of Polar codes, a coding technique proposed by E. Arikan in 2007, was initially implemented. Theoretical demonstrations have shown that the Shannon limit can be achieved for binary, discrete, memoryless channels through the utilization of a code with a straightforward algorithm. This has resulted in notable progress within the realm of channel coding. As a new coding technology, polar codes have attracted extensive attention in the wireless communication field and become one of the most attractive research hotspots in the coding field. This paper systematically expounds polar codes, analyzes the coding and decoding principles of polar codes, and compares them with Turbo codes and LDPC codes. In this study, polar code coding and decoding are simulated and implemented, and the impact of coding block length, coding rate, and iteration time variations on the performance of polar codes is explored. Through simulation and comparison, the performance, benefits, and drawbacks of these three codes are compared with the polar codes, turbo codes, and LDPC codes.

Keywords: channel coding, shannon limit; channel polarization, LDPC code, polar code.

1. Introduction

Information is subjected to interference from various aspects during the transmission process, including defects of various components of communication equipment and internal noise interference, various interferences in the channel, such as the fading of high-frequency channels, sky and electricity interference, etc. All these interferences will affect Information transmission reliability. If the information is directly sent to the channel without channel coding, the information received by the receiving end is unreliable because it does not have any capability of detecting and correcting errors. In communication, source coding, channel coding and data coding are often used at the same time. Channel coding can make the communication system obtain coding gain, thereby improving the reliability of communication. Communication systems usually have a given bit error rate index requirement, which is the bit error rate index requirement that the system can finally achieve after decoding. The corresponding bit error rate before decoding varies with different encoding methods.

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The channel coding method should have strong error correction ability, so as to allow a relatively large bit error rate before decoding, the corresponding bit energy noise density required for system transmission is relatively small, and the saved bits compared with non-coded transmission. The energy-to-noise density ratio is the coding gain achieved by the system.

2. Shannon theory

2.1. Shannon limit

As per the Noisy Channel Coding Theorem in the field of information theory, it is feasible to transmit data information with a significantly low probability of error, even in the presence of noise that may disrupt the communication channel, provided that the information transmission rate is less than the channel capacity. The Shannon-Hartley Theorem, also referred to as the Shannon Theorem, was first proposed by Claude Elwood Shannon in 1948, representing a surprising discovery. The term commonly used to denote this concept is the Fundamental Theorem of the Information Principle [1].

The theoretical maximum transmission rate of a channel under a given noise threshold is referred to as the channel capacity or Shannon limit of a communication channel.

This theorem outlines the best potential efficiency of error detection and correction under various levels of noise disturbance and data corruption, according to Shannon's 1948 assertion. The theorem merely tells one the optimal outcomes; it does not provide instructions on how to build a model for mistake detection. In the disciplines of communication and data storage, Shannon's theorem is frequently applied. The cornerstone of contemporary information theory is this theorem. Shannon just provided a general summary of the proof. Emile Feinstein was the first to present a thorough defense, in 1954.

According to Shannon's Theorem, information is conveyed at a rate of R over a noisy channel with channel capacity C, if

$$R < C$$

Then there is an encoding method that reduces the error that the recipient receives to a freely chosen, tiny number. This implies that, up until the speed limit C is achieved, information can theoretically be transmitted without error.

The reverse is equally important. If

$$R > C$$

Then, achieving an arbitrary low error rate is impossible. As a result, when the transmission speed exceeds the channel capacity, reliable information delivery cannot be assured. In no specific circumstance does the theorem state that capacity and speed are equivalent.

Simple processes such as "repeatedly send data 3 times, and use a voting system to select the same two values among the 3 when the data are different" are inefficient error correction methods, and there is no guarantee that the data block can be completely error-free ground transmission. Some advanced technologies such as Reed-Solomon coding technology and more modern coding technologies such as Turbo codes and LDPC codes are closer to the Shannon limit, but the computational complexity is very high.

2.2. The effect of Shannon limit on signal transmission

The presence of noise has the potential to corrupt one or more bits, as evidenced by the relationship between data rate, noise, and bit error rate. As the data rate increases, the length of these bits decreases, leading to a greater number of bits being impacted by a specific noise pattern. Consequently, when a noise value is present, an increase in data rate results in a corresponding increase in the bit error rate. The Shannon formula, which was formulated by the late mathematician Claude Elwood Shannon (1916–2001), provides a clear linkage between all of these aforementioned concepts.

As illustrated earlier, there is a positive correlation between data rate and the detrimental impact of extraneous noise. In the context of noisy environments, it is possible to enhance the accuracy of data reception by amplifying the signal strength given a specific noise level. The primary variable considered in this derivation is the signal-to-noise ratio (SNR or S/N), denoting the proportion of signal power to noise-contained power at a specific juncture in the transmission process. Typically, the signal-to-noise ratio is evaluated at the receiver stage, as it is the focal point for researchers to effectively extract the signal and eliminate undesired noise.

For ease of use, this ratio is usually expressed in decibels

$$SNR_{dB} = 10\, log_{10} \frac{P_{signal}}{P_{noise}} \tag{1}$$

It represents the amount by which the wanted signal exceeds the noise value, in decibels. The higher the value of SNR, the better the quality of the signal and the less the number of intermediate repeaters required [2].

The significance of the signal-to-noise ratio in digital data transmission lies in its ability to establish a maximum attainable data rate. It was concluded by Shannon that the equation governing the maximum capacity of a channel in bits per second (bps) is as follows:

$$C = B\, log_2 (1 + SNR) = B\, log_2 \left(1 + \frac{S}{N}\right) \tag{2}$$

The formula proposed by Shannon demonstrates the upper limit of attainable performance in a given communication system. Nevertheless, the achievable rates in real-world scenarios are considerably lower. One of the underlying assumptions of the formula is that the noise is limited to white noise, specifically thermal noise, while disregarding the effects of impulse noise, attenuation, and delay distortion. Despite the presence of ideal white noise, the current technological limitations, such as coding length and complexity, prevent the attainment of Shannon capacity.

The capacity referred to in Shannon's formula pertains to the transmission of data without errors. Shannon's theorem demonstrates that in cases where the information rate on a channel is less than its error-free capacity, it is theoretically possible to achieve the error-free capacity of the channel through appropriate encoding of the information. Regrettably, Shannon's theory does not offer a methodology for determining this encoding; however, it does establish a computational benchmark for evaluating the efficacy of real-world communication systems.

3. LDPC codes

3.1. The definition of LDPC code

A block code of dimensions (n, k) is classified as linear if the correlation between the supervisory element and the information element can be expressed as a linear equation.

The LDPC code graph, also known as a low-density parity-check code, is a linear block code that utilizes a generator matrix G to map an information sequence into a transmission sequence, or codeword sequence[3]. The generator matrix G and the parity check matrix H are completely equivalent. The null space of H consists of all codeword sequences C, that is,

$$H \times C^T = 0 \tag{3}$$

The sparsity of the parity check matrix H in the LDPC code is a notable characteristic. The row weight and column weight, also known as the number of non-zero elements in each row and column of the check matrix, are relatively small in comparison to the length of said row and column. LDPC codes are referred to as low density codes due to their sparse parity-check matrices, which contain a low density of non-zero elements. The closed loop distributions of coded bipartite graphs, also known as Taner graphs, vary across different LDPC codes due to the sparsity of the check matrix H and the application of distinct construction rules. The presence of a closed loop within the bipartite graph is a significant determinant of the decoding efficacy of LDPC codes. This attribute causes LDPC codes to exhibit distinct decoding performance when subjected to a specific category of iterative decoding algorithms that bear resemblance to the belief propagation algorithm [4].

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4. The development of LDPC codes

LDPC codes, which were introduced by Gallager in 1963, are a type of linear block code that utilizes sparse check matrices. Nonetheless, owing to insufficient computational capabilities, it remained underutilized for the subsequent three decades and disregarded by individuals. In 1996, a group of researchers, including D. MacKay and M. Neal, conducted a study on LDPC codes and determined that they exhibit exceptional performance, approaching the theoretical limit established by Shannon. Due to its low decoding complexity, parallel decoding, and error detection capabilities, this coding scheme has emerged as a prominent area of research in the field of channel coding theory.

The LDPC codes, which are non-regular in nature, as proposed by Mckay and Luby, present a generalization of the conventional LDPC codes. Non-regular LDPC codes exhibit superior performance not only in comparison to regular LDPC codes but also when compared to turbo codes. This code represents the closest proximity to the Shannon limit that is currently known.

Richardson and Urbank have significantly contributed to the advancement of LDPC codes. Initially, the authors suggest a novel encoding algorithm that effectively mitigates the substantial computational and storage demands of randomly generated LDPC codes during the encoding process. In addition, the theory of density evolution was developed by them, enabling the efficient analysis of the decoding threshold for a broad range of LDPC decoding algorithms. The simulation results indicate that the decoding threshold is stringent. Density evolution theory can be employed to facilitate the optimal performance of non-regular LDPC codes through design guidance.

5. Polar codes

5.1. Introduction to polar codes

The Polar Code is a method of forward error correction employed in the transmission of signals.

The fundamental aspect of the framework pertains to the management of channel polarization and the implementation of techniques on the encoding end to ensure distinct levels of dependability for each sub-channel. As the length of the code increases, certain channels may approach a state of ideal channelization, wherein their capacity approaches unity, while the remaining portion of the channel tends towards a state of pure noise channelization, with a capacity approaching zero [5]. The sole approach that can be rigorously demonstrated to achieve the Shannon limit is the selection of a channel with a capacity near 1 for the direct transmission of information.

Regarding decoding, a straightforward successive interference cancellation technique can be employed to decode the polarized channel. This method yields comparable performance to maximum likelihood decoding but with reduced complexity.

The concept of channel polarization was initially introduced by Professor Erdal Arkan from Bilken University in Turkey during the 2008 International ISIT Conference on Information Theory. According to this theory, he provided the earliest recorded instance known to humanity. Polar code is a channel coding technique that has been formally demonstrated to attain channel capacity.

In April 2016, Huawei declared that it had successfully accomplished the verification test of crucial air interface technologies in the initial stage of China's IMT-2020 (5G) promotion group. The company employed polar codes in all 5G channel coding domains. The convention took place in Las Vegas, Nevada, in the United States of America, and China. The Polar Code scheme was primarily advocated by Huawei, while the Low Density Parity Check Code (LDPC) scheme was predominantly promoted by Qualcomm in the United States, and the Turbo 2.0 scheme was primarily advocated by France.

5.2. Algorithms and principles of polar codes

Transition probability: a binary input discrete memoryless channel (B-DMC) can be represented as $W : X \rightarrow Y$, X is the set of input symbols, Y is the set of output symbols, and the transition probability is $W(y \mid x), x \in X, y \in Y$. Since the channel is a binary input, the set $X = \{0, 1\}$;Y and

W (y | x) are arbitrary values. The channel after N uses of channel W can be expressed as WN, Then the transition probability of channel $W_N \rightarrow Y_N$ is, $W_n(y1_N|x1_N) = \prod i = 1NW(y|x)$.

Channel polarization: channel polarization is divided into two stages: channel association and channel splitting. For polar codes of length N=2^n, it uses N independent copies of channel W to perform channel union and channel splitting to obtain new N sub-channels $\{WN(1), WN(2), \ldots, WN(N)\}$. As the length of the code increases, the split channel will tend towards two extremes. One portion of the split channel will approach a channel with ideal characteristics, characterized by a lack of noise and a channel capacity that approaches unity. Conversely, the other portion of the split channel will approach a channel with high levels of noise, characterized by a channel capacity that approaches zero.

We mainly study the binary discrete memoryless channel, and abstracting the above channel model (including BEC, BSC, AWGN), we can get the following channel transmission model:

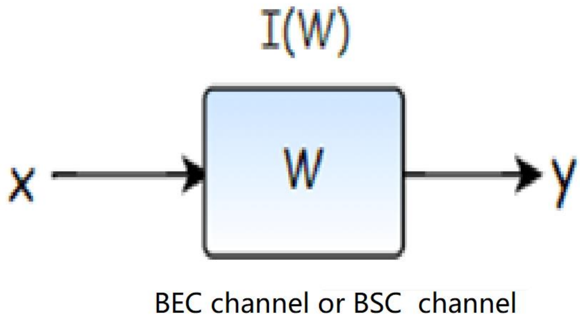

Figure 1. BEC channel or BSC channel.

Channel association: Channel union is a process of performing butterfly-shaped XOR operation on multiple sub-channels. For polar codes with code length N=2, we can mix the two channels by the following butterfly XOR operation:

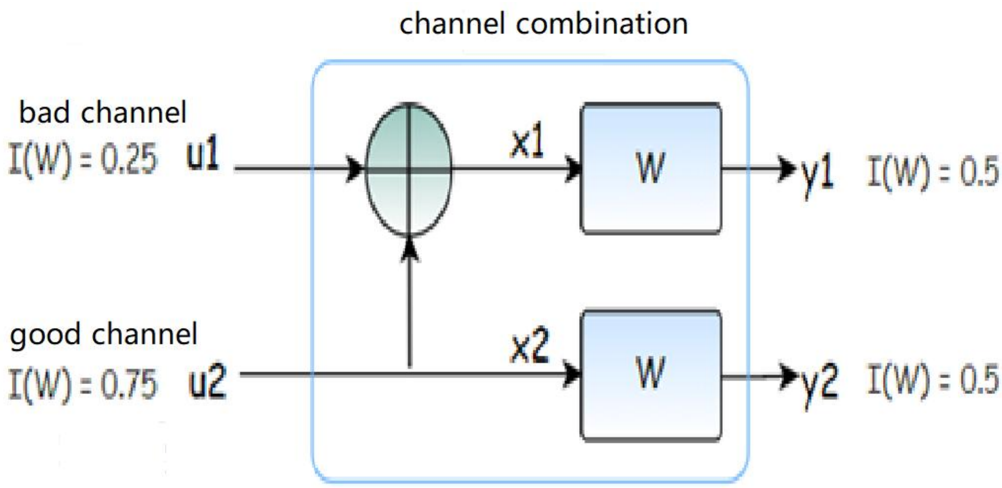

Figure 2. Channel combination.

The depicted figure illustrates that the amalgamation of channels results in a polarization of the channel capacity of channels possessing distinct coordinates. Specifically, the channel capacity I (W) of one bit experiences an increase, while the channel capacity I (W) of the other bit undergoes a decrease. A channel with a small capacity is called a poor channel, and a channel with a large capacity is called a good channel. Because after the channel combination is performed, and because the channel u1 on the left is required, u1 can only be obtained when both channels y1 and y2 on the right side are received at the same time, so the channel capacity of u 1 is the channel y. The product of channel capacity of y1 and y2; correspondingly, for channel u2, the channel cannot be received only when both y1 and y2 cannot be received, so its channel capacity I (W) is 2 ∗ 0.5 − 0.5^ 2.

We can also use a two-dimensional table to calculate the probability of their transmission:

Table 1. Probability of transmission.

y1	y2	u1	u2
√	√	√	√
√	x	x	√
x	√	x	√
x	x	x	x

It can be found from Table 1 that for the signals y1 and y2 received by the receiver, there are a total of 4 cases, X indicates that the channel has an error and the channel has not been received; √ indicates that the channel has received the channel. For sub-channel u1, among the four cases, only one of the four cases can accept u1, that is, the case where y1 and y2 are received at the same time, so the channel capacity is 1/4; and for u2, as long as y1 or y2 can be received. According to the channel polarization theory, we already know that the channel capacity of the channel u1 is relatively small in the process of polarization, we will use it as a frozen bit, fill it with 0, and not transmit information bits, only the frozen bits are transmitted, so we can also derive u2 without receiving y2.

For the code length of N=4, we can recursively carry out the channel combination, as shown in the figure, but compared with the polar code of the code length of N=2, we need to increase the channel combination process once:

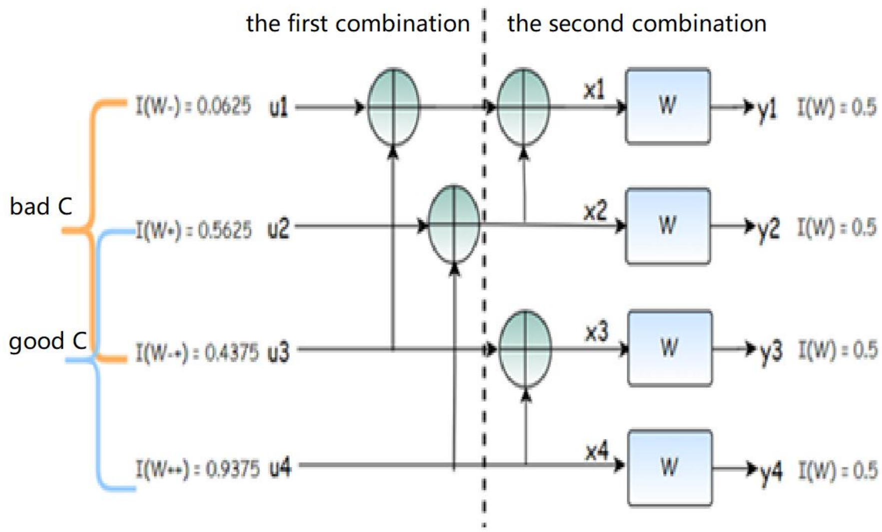

Figure 3. The channel combination process.

6. Comparison of LDPC codes and polar codes

The advantages of polar codes:

1. The performance of Polar codes approaching the Shannon limit has strong theoretical support.
2. The polar code has a clear coding method.

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3. The coding and decoding complexity of polar code is relatively low.

4. The polar code adopts a suitable decoding method such as (CA-SCL algorithm), and its performance can surpass the best LDPC code and Turbo code.

Disadvantages of polar codes:

The high degree of parallelism in the polar code decoding process is not easy to achieve, resulting in a relatively large delay. The reason is that the mechanism of the SC decoding algorithm is bit-by-bit decoding [6].

Compared with another near-Shannon-limited code, the Turbo code, the LDPC code has the following advantages:

1. The LDPC code decoding algorithm is an iterative decoding algorithm that operates in parallel and is founded on a sparse matrix. The computational requirements of the decoding algorithm for this code are comparatively lower than those of the Turbo code. Additionally, the parallel structure of this algorithm makes it more hardware-friendly and simpler to implement. Hence, in communication applications with high capacity, LDPC codes exhibit greater advantages [7].

2. The LDPC code's code rate exhibits a high degree of flexibility and can be constructed in an arbitrary manner. In order to attain elevated bit rates, turbo codes necessitate the implementation of puncturing. Therefore, the selection of puncturing patterns must be meticulously evaluated to avoid incurring a significant decline in performance.

3. Low-Density Parity-Check (LDPC) codes exhibit a reduced error rate and are suitable for deployment in wired communications, deep space communications, and disk storage sectors, where stringent bit error rate requirements are prevalent. The error correction capability of Turbo codes is approximately 10. In instances where similar circumstances arise, it is typically necessary to incorporate the inner code within the outer code in order to fulfill the necessary specifications.

7. Conclusions

In this paper, Shannon's theorem is used as a starting point to discuss the various factors that affect signal transmission in the channel, and the concept of channel coding is introduced. Then, several basic channel coding methods are introduced, they are LDPC code, and polarization code, among which polarization code is the main 5G coding method used by Huawei. This paper mainly introduces the algorithm and implementation of polarization code, and how to divide the channel into good channel and bad channel by logical operation and iteration to improve the channel efficiency. Finally, the advantages and disadvantages of polarization code and LDPC code are compared.

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