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An enhanced single-disk fast recovery algorithm based on EVENODD encoding: Research and improvements

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Abstract. In the wake of rapid advancements in information technology, the need for reliable and efficient data transmission continues to escalate in importance. Channel coding, as a pivotal technology, holds significant influence over data communication. This paper delves into the fundamental technologies of channel coding and their prominent applications. Initially, the study introduces the current research status and the significance of channel coding. Following this, a comprehensive illustration and introduction to the classical coding methods of channel coding are provided. Concluding this exploration, the paper elucidates on the prevalent applications of different channel coding methodologies in scenarios such as the Internet of Things, 5G, and satellite communication, using real-world examples for clarity. Through this comprehensive research, readers gain an understanding of the key technologies underpinning channel coding, as well as the diverse applications that typify its use. By casting light on the practical implications of channel coding in contemporary technological contexts, the paper serves as a valuable resource for those seeking to deepen their knowledge and understanding of this pivotal field.

Keywords: channel coding, internet of things, 5G, satellite communications.

1. Introduction

In the contemporary digital era, the transmission and exchange of information have become essential across various industries and departments. The demand for data transmission in modern society continues to grow. Whether considering the internet, mobile communication, television broadcasting, the Internet of Things, or intelligent transportation, reliable and efficient communication systems are of vital importance to their normal operation and development. During the process of data transmission, the transfer is often affected by channel noise and interference, which leads to an increased data transmission error rate [1]. To achieve reliable data transmission within such a complex environment, it becomes necessary to utilize channel coding technology to correct and detect transmission errors. In practice, communication systems in different scenarios often have diverse transmission requirements and restrictions. Appropriate channel coding can be optimized according to the characteristics of specific channels, fully leveraging the potential of the channels. For instance, in wireless communication, channels often face multipath effects and fading phenomena. The appropriate coding can enhance the reliability of data transmission and reduce resource consumption, such as bandwidth and power, through anti-fading measures and suppressing multipath interference. In order to meet channel coding requirements in different scenarios, this paper explores the feasibility and effectiveness of various

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encodings in diverse scenarios by understanding the use requirements of various encodings and scenarios.

2. Relevant theories

2.1. Channel coding

Channel coding stands as a pivotal technique designed to augment the reliability of data transmission and correct errors that could manifest during the process. In a communication system, data undergoes transmission through a channel susceptible to a variety of influences such as noise, interference, and fading. These elements can introduce errors into the transmitted data. The purpose of channel coding is to metamorphose the original data by inserting redundant information, culminating in encoded data. The utilization of channel coding notably enhances the reliability of data transmission as errors can be identified and rectified, ensuring the integrity of the transmitted information.

In 1948, Bell Labs' C.E. Shannon published "A Mathematical Theory of Communication" [1], a defining paper in modern information theory that established the foundation for the field of information and coding theory. This pioneering work signified the inception of a new discipline. Shannon's paper presented a key insight: the transmission rate of information is dictated by the channel capacity. As long as the transmission rate remains beneath the channel capacity, reliable communication can be achieved through error control techniques. This fundamental principle transformed the understanding of communication systems and facilitated further advancements in the field. Consequently, error-proof coding technology has attracted widespread interest and value. Prominent error-resistant coding techniques can be bifurcated into Automatic re Quest-for-Repeat and Forward-Error-Correction. In the Automatic re Quest-for-Repeat scheme, the channel code only detects whether the received code word contains error bits, and requests the sender to resend the code word in the event of an error. In the Forward-Error-Correction scheme, the coding task is not just to identify errors, but also to rectify them. This necessitates a particular design of the encoder, such coding is called error detection and error correction code. In the Automatic re Quest-for-Repeat scheme, the whole packet requires retransmission when the packet is sent incorrectly. This process is inefficient and cumbersome in real-time mobile communication. Modern wireless communication often employs Forward-Error-Correction schemes that can correct error bits in real-time. In 1950, R. Hamming proposed the Hamming code, the first practical error coding scheme capable of detecting and correcting one error element. At the transmitting end, the encoding scheme divides the input bit information sequence into groups, and each group of bit information obtains the corresponding check bit code word through the Exclusive OR operation. At the receiving end, the decoding result is also verified by the Exclusive OR operation, and the error check group and the error bit are inverted and corrected. Following this, M. Golay proposed the Golay code, referring to the idea of Hamming code, which can correct three random error bits. In 1957, Eugene Prange proposed cyclic code, whose generating matrix and check matrix possess cyclic characteristics, strict algebraic structure and simple implementation of the coding circuit. In 1960, Bose and Ray-Chaudhuri improved on the basis of the cyclic code and developed a more robust error correction Bose-Chaudhuri-Hocquenghem code. This code has exceptional performance and inherited the simple structure of cyclic code, and was widely adopted in various communication systems of that era. A parallel concatenated convolutional code referred to as Turbo code was proposed. Turbo code was the first to incorporate the concept of feedback in the circuit into the decoding structure, and its ingenious coding and decoding structure greatly elevated the performance of channel coding and approached the Shannon limit. Owing to its low coding complexity, Turbo code has evident advantages in the performance of short and medium codes, and the encoding and decoding technology is relatively mature, making Turbo code widely employed in practical mobile communication systems.

Low-Density Parity-Check Code was first suggested by Dr. Robert G. Gallager at the Massachusetts Institute of Technology in 1963. The performance of Low-Density Parity-Check codes is quite remarkable, almost approaching the Shannon limit, and can be applied to any channel. However, its decoding algorithm is exceedingly complex, and the research technical conditions at that time were

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limited, and the Low-Density Parity-Check code did not attract the attention of most scholars after it was proposed. It was not until 1993 when Berrou and others made the breakthrough discovery of Turbo codes. Building upon this advancement, MacKay, Neal, and others revisited Low-Density Parity-Check codes around 1995. They proposed a decoding algorithm that gained widespread acceptance. In the subsequent decade, researchers have made breakthroughs in the study of Low-Density Parity-Check codes, bringing the performance of Low-Density Parity-Check codes closer to the Shannon limit, and practical applications have become feasible. Until now, the research on Low-Density Parity-Check code has been very mature, and has entered the standard of wireless communication and other related fields.

2.2. Specific coding

2.2.1. Hamming code. Hamming code is a commonly used error detection and correction coding scheme, proposed by Richard W. Hamming in 1950 [2].

The basic principle of Hamming code is to combine information bits and check bits into a coded word by adding check bits. Specifically, for a given k bits of information, the number of redundant bits needs to be selected to satisfy the relation: $2^r \geq k + r + 1$. Thus, the total length of the coded word is n = k + r. In the construction of Hamming codes, check bits are arranged at specific locations in the coded word in order to detect and correct errors during transmission. The positions of these check bits are the power positions of 2 in the binary representation (1, 2, 4, 8, etc.). Each check bit is responsible for checking a specific set of information bits.

In terms of error detection, by calculating the parity of the check bits and comparing them with the actual received check bits, it is possible to determine whether there is an error. If an error occurs, the location information of the check bit can be used to locate and correct the error.

The advantage of Hamming code is that it can detect and correct multi-bit errors and has low codec complexity. However, its main disadvantage is that it has high redundancy and certain limitations in error correction ability.

Hamming codes have gained significant popularity and find extensive utilization in computer memory and communication systems. Particularly in computer memory, these codes play a crucial role in detecting and correcting bit errors that may occur within unit memory components like RAM. In the field of communications, Hamming codes are used for error control in data transmission to ensure reliable transmission of data across radio, fiber optic and wired communication links.

In summary, Hamming code is a classic error detection and correction coding scheme, which realizes error detection and correction in the process of data transmission by adding check bits. It has low codec complexity and is widely used in computer memory and communication systems.

2.2.2. BCH code. The BCH Code (Bose-Chaudhuri-Hocquenghem Code) is a widely used linear block code scheme for error-correcting coding, independently proposed by R. C. Bose and D. K. Ray-Chaudhuri in the early 1960s [3]. It was further developed by A. Hocquenghem.

BCH codes can detect and correct a certain number of errors in the transmission process by using primitive polynomials to construct code words. It has good error correction ability and decoding efficiency, and is widely used in data storage, communication system and other fields. The generating polynomial of a BCH code is an indecomposable polynomial of low degree where the roots satisfy specific mathematical properties. By combining these primitive elements, a series of BCH codes of different lengths can be generated. During decoding, the BCH code is decoded using an error-correcting algorithm whose ability is related to the length of the code word. Common decoding algorithms include Berlekamp-Massey algorithm, Forney algorithm and so on. By decoding and correcting the received code words, the original data block can be recovered. The characteristics of BCH code are as follows:

1. powerful error correction ability: BCH code can detect and correct the transmission error of multiple error bits, with high error correction ability.

2. simple decoding algorithm: the decoding algorithm of BCH code is relatively simple, with low decoding complexity.

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Codeword length variability: By adjusting the number of polynomials generated, BCH codes of different lengths can be generated to meet different application requirements.

3. BCH code is widely used in a variety of storage media and communication systems, such as disk drives, CD-ROMs, radio communications, etc. It plays an important role in the protection of error correction in the process of data transmission and improves the reliability and integrity of data.

In summary, BCH code is a linear block code error correction coding scheme, with strong error correction ability and low decoding complexity. It is widely used in data storage and communication systems, providing reliable protection and error correction capabilities for data transmission.

2.2.3. Urbo code. Turbo Code is a high-performance error-correcting coding scheme proposed by Claude Berrou, Alain Glavieux and Pierre Thitimajshima in 1993 [4]. Turbo code has excellent error correction performance while approaching the channel capacity through iterative decoding.

The basic principle of Turbo code is to use two or more encoders and an iterative decoder. During the encoding process, the data to be transmitted is fed into two separate encoders and produces two distinct sequences of code words. When passing through the channel, these two code word sequences are interwoven according to certain rules.

In the process of decoding, the method of iterative decoding is used to compare the received code word with the previous decoding result, and make corrections according to the comparison result. The iteration process is repeated several times until a preset number of iterations is reached or specific stopping criteria are met. The core of Turbo code is an iterative decoding algorithm, which uses a technique called iterative decoding. Iterative decoding is modified continuously by feeding the previous decoding results into the next round of decoding as feedback. This iterative correction process can effectively improve the performance of error correction. The Turbo code has the following important features:

- achieve coding efficiency close to the channel capacity, and can transmit more information under limited signal-to-noise ratio.
- has a high error correction ability, can effectively detect and correct the error generated in the transmission process.
- through iterative decoding, error correction performance can be further improved, close to the limit of channel capacity.

Because of its excellent performance, Turbo codes are widely used in many communication systems, such as mobile communications, satellite communications, digital television, wireless local area network (WLAN) and so on. In 4G mobile communication standard, Turbo code is adopted as the error correction coding scheme of downlink. In summary, Turbo code is a coding scheme with strong error correction ability, and uses iterative decoding technology to approach the performance of channel capacity. It is widely used in many communication fields and provides reliability and efficiency for data transmission.

2.2.4. LDPC code. LDPC is an error-correcting coding scheme proposed by Robert G. Gallager in 1962. LDPC codes have excellent error correction performance and low decoding complexity by means of sparse check matrix [5].

The core idea of LDPC code is to combine information bit and check bit to form code word by introducing sparse check matrix in the process of coding. In the check matrix, most of the elements are zero, and the distribution of non-zero elements is sparse. This structure allows LDPC codes to be decoded using efficient iterative Decoding algorithms, such as Message Passing Decoding.

In the encoding process, the LDPC code uses the check matrix to perform linear operations on the transmitted data and generate check bits. The generated code word consists of information bit and check bit. When decoding, the iterative decoding algorithm is used to backinfer the received code words, calculate and correct the possible errors. The iterative decoding algorithm iteratively corrects the message between the check bit and the information bit until the stop criterion is satisfied. The commonly used iterative decoding algorithms include Belief Propagation (BP) algorithm, Sum-Product algorithm, etc.

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LDPC codes have the following features:

- low decoding complexity: due to its sparse check matrix structure, LDPC code decoding algorithm has a low complexity, suitable for real-time applications.
- excellent error correction performance: LDPC code performs well in the performance of close to the channel capacity, and can effectively detect and correct errors generated in transmission.
- flexibility: the LDPC code check matrix can be designed and adjusted according to different requirements to adapt to different channel conditions and performance requirements.

Due to its excellent performance and flexibility, LDPC codes are widely used in many communication systems, such as satellite communications, optical fiber communications, wireless local area network (WLAN), Blu-ray disc and so on. In the 5G mobile communication standard, LDPC code is adopted as the error correction coding scheme of data channel.

In a word, LDPC code is an error-correcting coding scheme implemented by sparse check matrix, which has low decoding complexity and excellent error-correcting performance. It is widely used in communication systems and plays an important role in high-speed data transmission and wireless communication.

2.2.5. Polar code. Polar Code is a coding method used in communication systems, proposed by Arikan in 2008 [6]. Polarization code transforms a group of independent sub-channels with the same channel conditions into a stable group of high performance channels and a poor group of low performance channels through a specific linear transformation. This encoding method has been theoretically proven to achieve Shannon capacity.

The main idea of polarization code is to construct code words by arranging sub-channels with different reliability, so as to achieve high reliability communication. Specifically, it utilizes a recursive algorithm to progressively "polarize" the channel by repeatedly applying a matrix transformation operation, converting the original binary input sequence into a series of code words with varying reliability. The code word corresponding to the more reliable subchannel is almost error-free in transmission, while the code word corresponding to the less reliable subchannel may have more errors in transmission. The characteristics of polarization code are as follows:

- polarization code can be flexibly designed according to different communication scenarios and needs. By choosing a suitable construction algorithm, the coding with different length and error-correcting ability can be realized.
- The decoding algorithms of polarization codes are characterized by low complexity, especially the decoding algorithms based on Successive Cancellations (SC). This makes the polarization code have high real-time and feasibility in practical application.
- polarization code in the noise and interference of the channel shows a strong anti-interference performance. By adding a proper number of check bits, error and noise in the channel can be effectively combated.

Polarization codes have been widely used in many communication standards, including the fifth generation mobile communication standard (5G) and satellite communications. It has great potential in high-speed, low latency and high reliability communication systems, and provides an important coding basis for the development of future communication technologies.

3. Application scenario research

3.1. Internet of things scenario

The Internet of Things (IoT) is a technological ecosystem that enables the connection and communication between the physical and digital realms through internet connectivity. It facilitates intelligent interconnection and data exchange among devices. At its core, the IoT aims to link diverse devices and objects to the internet, enabling them to perceive their environment, gather data, and make independent decisions. These devices can establish an internet connection using either wireless or wired methods. They can then store, process, and analyze data utilizing cloud platforms, thereby enhancing the intelligence, convenience, and efficiency of various applications. Ultimately, the IoT empowers a seamless integration between the physical and digital worlds, fostering a new level of connectivity and enabling transformative capabilities.

IoT devices are extensively utilized in various domains, including consumer, commercial, industrial, and infrastructure sectors. In the IoT industry, a significant volume of image data is collected, stored, and transmitted by collaborative, low-power devices. For example, surveillance cameras in smart cars capture surveillance images that contribute to this data. Consequently, there is a rise in the number of image files being released and distributed across multiple servers. However, in cases where malicious actors tamper with IoT data, errors may go unresolved, leading to data loss. To address these challenges, Lizhi Xiong proposed a secure and reliable secret image sharing system based on Internet of Things Extended Hamming code (RSIS) [7]. RSIS leverages the distributed architecture of IoT to provide secure information sharing. The hidden images are divided into steganographic images, which can be distributed to multiple servers located outside the IoT network, making it challenging for attackers to detect them. Using RSIS, the data is encoded and embedded within the steganographic images using Hamming code, allowing for a high probability of detecting any potential spoofing attempts.

Now, the demand for IoT applications in current communication networks has been growing. To meet the needs of low-cost and low-power IoT applications, various IoT standardization bodies have proposed different technologies to adapt to this trend. One such technology is Narrowband IoT (NB-IoT), which utilizes Turbo codes with modern error correction coding techniques to achieve high error rate performance close to Shannon's theoretical limits. Turbo codes have demonstrated excellent performance characteristics and are widely applied in many communication standards. However, the computational complexity of Turbo decoders is significantly higher than other modules in NB-IoT receivers, particularly when dealing with higher data rates and low-latency communications. To enhance the flexibility of the uplink system, Mohammed Jajere Adamu [8] and his team proposed an improved approach to Turbo channel decoding. They introduced a frequency domain equalizer (FDE) into their Soft Interference Cancellation (SIC) scheme for uplink NB-IoT systems. This method employs an iterative detection process that exchanges soft decision information between the FDE and Turbo channel decoder to eliminate inter-symbol interference (ISI). Through extensive simulation evaluations of Mean Square Error (MSE) and Block Error Rate (BLER) performance, the researchers have put forward a robust scheme aimed at improving the reliability of user device (UE) data transmission in NB-IoT systems while simultaneously reducing computational complexity. This research offers valuable insights for the development of NB-IoT systems, enabling them to better adapt to the increasing demands of IoT applications.

3.2. 5G scenario

In the new era of information development, people's demand for Mobile Communication has increased significantly, so the 5th Generation Mobile Communication Systems (5G) has been rapidly developed in a short time, and 5G will play an increasingly important role in the future. 5G has higher requirements for information transmission rate, reliability and delay, and channel coding technology is one of the main wireless transmission technologies to meet these needs. In order to receive signals in noisy channels correctly and lossless, new channel coding technologies such as Polar code and LDPC code are gradually proposed, which greatly improves the channel capacity of 5G communication. At the same time, these technologies have also been rigorously demonstrated to achieve the Shannon limit.

Aiming at the serious performance loss of 5G LDPC quantized minimum sum decoding algorithm, Shao proposed a Modified Adapted Min-Sum (MAMS) decoding algorithm [9]. First, based on the situation that the decoding performance is more sensitive to the offset factor in the check node update function when the row degree and column degree of the 5G LDPC check matrix are low, different check node update functions are adopted according to the different values of the row degree and column degree to improve its error correction ability. Then, the third smallest value in the message passed by the variable node to the check node is introduced to adjust the offset factor to reduce the decoding error rate. Finally, by setting the threshold of iteration times, check node update functions of different complexity are adopted in the iteration process to cut down the decoding complexity. At the same time, in view of the hardware implementation of 5G LDPC code coders, he also completed the hardware design and implementation of supporting multi-rate compatible coders.

Polarization code was proposed in 2009, due to its excellent performance and huge potential, a large number of researchers invested in it, so in 2016, polarization code was confirmed for the 5th Generation Mobile Communication system. Aiming at the problem of poor error correction performance due to low error detection efficiency of parity-assisted polarization codes (PC-polar codes for short), Zhang proposed a novel coding algorithm for Cyclic Redundancy Check (CRC) code-assisted PC-polar codes [10]. The algorithm uses PC bits and frozen bits with high Hamming weight to replace the information bits with low Hamming weight to optimize the distance spectrum of the polarization code, and combines the five-bit cyclic shift register to optimize the check function of PC code, then adds the CRC code with high error detection efficiency to the PC-polar code, and finally determines the number of the two check codes by the control variable method. At the same time, a Successive Cancellation List (SCL) decoding algorithm based on key sets is proposed to solve the problem of high computational complexity in PC-polar code decoding. In this algorithm, the polarization code is decomposed into 6 sub-polarization codes, and the key set is constructed by selecting the information bits with low Hamming weight from each sub-polarization code, and adding the information bits with low polarization weight value to further improve the key set.

3.3. Satellite communication scenario

As we enter the era of 5G, communication systems are advancing towards high speed, low latency, and superior reliability. Nevertheless, 5G ground base stations are confronted with challenges such as cost and physical conditions, which restrict them from providing communication services to remote mountains, oceans, deserts, and other non-urban areas. Moreover, ground communication networks are susceptible to damage during natural disasters. Low-orbit satellite communication networks, however, cover a vast range, are less impacted by natural conditions, and can still provide services amidst natural disasters. Currently, setting up a low-orbit satellite communication network and integrating it with the terrestrial mobile network offers an effective solution to the issues present in ground communication networks. Satellite communication networks utilize satellites as relays to facilitate information transmission. Given the long communication distance from the terminal, these networks experience significant signal attenuation and large Doppler shifts, leading to low reliability. Channel coding is one strategy to enhance the reliability of the communication system. Polar code, theoretically proven to reach the Shannon capacity limit, boasts excellent performance, thereby establishing it as a channel coding scheme for low-orbit satellite communication.

Taking low-orbit satellite communication as an application scenario, Gao analyzed the encoding and decoding algorithm and construction algorithm of Polar code. He proposed an improved Polarization Weight (PW) construction algorithm for block fading channels [11]. The performance of Polar code was simulated under block fading (BF) channel conditions and compared with two Low-Density Parity-Check codes suggested by the Consultative Committee for Space Data Systems (CCSDS) for current low-orbit satellite communication. Satellite navigation represents another typical application in satellite communications. To further enhance the interference resistance of navigation signals, Turbo code, known for its superior performance, is adopted as the channel coding technology in the new generation satellite navigation system. Among several Turbo decoding algorithms, the logarithmic Maximum A Posteriori (LOG-MAP) decoding algorithm excels in performance and complexity. However, the decoding delay of this algorithm is proportional to the frame length. In the satellite navigation receiver, when the frame length is long, the number of tracking channels is large, and the decoding clock is not fast enough, the LOG-MAP decoding algorithm becomes unsuitable. Xue et al. added a sliding window operation to the LOG-MAP decoding, significantly reducing the decoding delay and the Random Access Memory (RAM) resources required by the decoding module [12].

4. Conclusion

This treatise engages in a detailed discourse surrounding the prevalent coding techniques and their respective application environments in the realm of channel coding. By elucidating the current status and consequential importance of channel coding, it seeks to provide readers with a comprehensive understanding of the critical role channel coding plays within data communication. The role of channel coding, essentially, is to safeguard data transmission in the face of potential interference and noise disturbances, ensuring high-quality data exchange. This function is pivotal for the smooth operation of any modern digital communication system, from Internet and mobile communications to television broadcasting and more. In scenarios plagued by significant noise, a well-chosen channel coding can even aid in error correction, thus enhancing the reliability of data transmission. To further solidify this understanding, the paper also delves into the typical implementations of various channel codes within specific settings such as the Internet of Things, Fifth-Generation telecommunications technology, and satellite communication. By illustrating these practical examples, it aims to shed light on the feasibility and effectiveness of applying different coding methodologies across diverse scenarios.

In essence, the study of channel coding and its various implementations can prove to be a vital resource for individuals involved in the design and operation of communication systems. By providing this comprehensive exploration, the paper encourages a deeper appreciation of the importance of channel coding, and its vast potential in optimizing modern communication systems.

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